Soil Water Regimes of the Glendhu Experimental Catchments

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Abstract

The Otago block mountains are important water supply areas with their abundant water yield attributed to conservative water use by narrow-leaved snow tussock (*Chionochloa rigida),* the dominant vegetation cover of the region. This study looks at three aspects of the soil hydrology of the Glendhu experimental catchments, east Otago, New Zealand: soil water regime changes following afforestation of the tussock grasslands; a comparison of soil water regimes with topographic position in order to identify possible saturated overland flow generation sites; and some characteristics of a peat wetland that is typical of those that occupy gullies in the region.

Several sites were set up in the forested and the tussock catchments, and depending on position, contained tensiometer nests, neutron probe access tubes and water table observation wells. Data were collected between 29/3/93 and 19/5/94 and revealed much drier conditions under forest cover, with saturation not occurring in the A horizon throughout the study period. Using tussock catchment sites for topographic comparison, a downslope increase in water content was found on the interfluve, while saturation persisted for longer periods of time at headwall sites where subsurface convergence resulting from the concave planar morphology occurs. Wetland water tables only fluctuated 27.5 *cm* during the study period, and do not appear to be sustaining the high baseflow that occurs from the catchment.

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Introduction

1.1 Landuse change

Investigations of the hydrological effects of vegetation change have mainly been in catchment experiments. The paired catchment design has been favoured (Bosch and Hewlett, 1982), and there have been many long term studies such as those carried out at the Hubbard Brook and Marcell experimental forests in northeastern USA (Hornbeck *et al.*, 1993).

The catchment scale effects on evaporation and runoff as a result of replacing tall vegetation with short vegetation are reasonably clear, with replication of this type of study throughout the world showing consistent results: water yield increases when tall vegetation is replaced by short vegetation, and the changes increase with mean annual rainfall. Large scale catchment studies provide a valuable context for process oriented research, as they supply important verification data.

Few studies have been carried out at the plot scale on the hydrological effects of vegetation modification. Plots are normally too small to be representative of large areas, though small scale work does allow information on the mechanisms that control change to be examined.

Detailed study of evaporation characteristics of different vegetation types (e.g. McNaughton and Jarvis, 1983; Miranda *et al.*, 1984), have helped in modelling regional effects, but other factors affecting the hydrological response, such as the soil water status, have received little attention. The British appear to be one of the few nations investigating vegetation-soil water relationships at the plot scale with studies such as Pyatt and Smith (1983) and King *et al.* (1986) allowing a better understanding of the processes involved with vegetation modification. Future research in landuse hydrology will have increasing emphasis on processes, in order that predictive models may be parameterised for a whole range of environments.

1.2 Glendhu experiments

The schist block mountains of Otago are important water supply areas, so landuse change is an important issue because of the effects it may have on water yields. The Glendhu catchments (Figure 1.1) have been the site of several studies into the hydrological processes of this landscape. Previous studies have primarily related to water and sediment yield on the catchment scale, with the exception of the lysimeter study by Campbell (1987) which measured evaporation from narrow-leaved snow tussock (*Chionochloa rigida*), the dominant vegetation cover.

Pearce *et al.* (1984) examined the water balance of the Glendhu catchments and concluded that evaporation losses from the native grasslands were substantially smaller than would be predicted by the Penman or other estimation methods. The work of Campbell (1987, 1989) and Campbell and Murray (1990) on tussock evaporation has also indicated quite low evaporation rates.

Baseflows at Glendhu have been found to be sustained at moderate levels for long periods of time when compared with the discharges from other catchments with different vegetation covers (Pearce *et al.,* 1984). Pearce *et al.* (1984) considered this may be related to the low transpiration demand by *Chionochloa rigida*. Bonell *et al.* (1990) also conducted an isotope tracer study of runoff production at Glendhu. Quickflow and baseflow were found to be dominated by pre-event rainfall from unconfined soil and ground water, as translatory processes released water to the stream channel.

A paired catchment study of afforestation of the tussock grasslands was set up in 1979, with *Pinus radiata* being planted on 67% of the treatment catchment. Higher interception from the tree canopy is believed by Fahey and Watson (1991), and Murray *et al.* (1991), to be the main reason for decreased baseflow and quickflow from the *Pinus radiata* catchment. Vegetation effects on soil water status may play an important role in the runoff generation in the catchments. Increased evaporation by conifers may reduce storage of water in the soil profile, and therefore reduce the role of saturated overland and translatory flow processes.

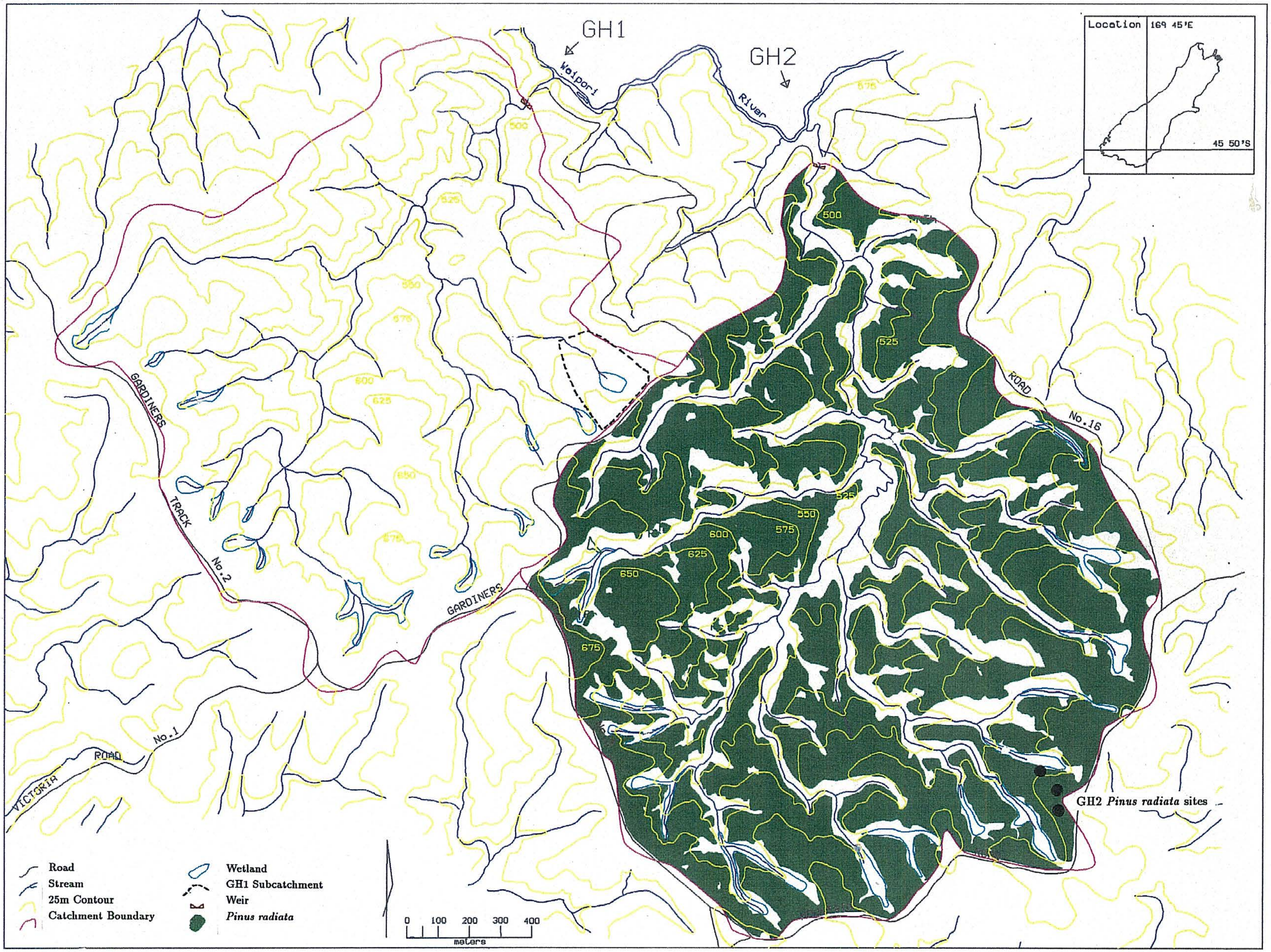

FIGURE 1.1: Glendhu experimental catchments (GH1 *Chionochloa rigida* catchment on left, GH2 *Pinus radiata* catchment on right). The GH1 headwater subcatchment and GH2 instrument locations are also marked.

1.3 The present study

This is a pilot study into the soil water regimes at Glendhu under *Pinus radiata* and *Chionochloa rigida*. Soil water content and potentials were monitored over a single summer to determine whether there are differences under the two vegetation types, in terms of storage capacity, storage availability, and vertical flow patterns. Interpretations are in terms of patterns of wetting and drying, and also the response to particular storms. Soil water regime variation with topography is a second aspect of the study, with the objective of identifying source areas for runoff generation. The third facet involves a small gully peat wetland that is typical of those that fill depressions in this landscape. It has been suggested that these wetlands are the source of the substantial baseflows in the region (Bonell *et al.,* 1990; O.C.B. and R.W.B., 1983), and the present study related water levels to rainfall, stream discharge, and the soil water status of the surrounding slopes.

The main objectives of this study were:

- to investigate soil water contents and moisture flux differences between the different vegetation covers of the Glendhu experimental catchments;
- to investigate the topographical effect on soil moisture, and identify possible source areas for runoff generation; and
- to describe hydrological characteristics of a peat wetland in the Glendhu catchment and compare the water level fluctuations with rainfall, stream discharge, and soil water status of the surrounding slopes.

2

Background to the study

2.1 Comparison of forest with grasslands

Landuse can have profound effects on evaporation, infiltration, and quantity of water available for streamflow (Wu and Haith, 1993). Conversion of native grasslands to exotic forestry is a world wide phenomenon and has been common in New Zealand.

Many studies have investigated the effects of afforestation on water yield (e.g. Smith, 1987; Fahey and Watson, 1991; Kienzle and Schulze, 1992; Smith and Scott, 1992), and many more studies have looked at the effects of deforestation on water yield (e.g. Hewlett and Hibbert, 1961; Lewis, 1968; Patrick and Reinhart, 1971; Harr, 1979).

2.1.1 Paired catchment studies

The use of paired catchments to study forest treatment effects on catchment hydrology began at Wagon Wheel Gap in Colorado, U.S.A. in 1909 (Bosch and Hewlett, 1982) and reached its peak in the 1960s (Hornbeck *et al.,* 1993). Hibbert (1967) reviewed the results of 39 short term studies and reported that: water yield is increased after a reduction in forest cover; decreased water yield occurs after establishment of forest cover on sparsely vegetated land; and that the response to treatment is highly variable, and usually hard to predict. Bosch and Hewlett (1982) updated that review with the addition of a further 55 studies. The results remained consistent, though it is now clear that the direction of change is predictable, with coniferous forest, deciduous forest, hardwood forest, bush and grass cover giving progressively larger water yields.

Fahey and Watson (1991) examined the short term changes in water yield following afforestation in the Glendhu paired catchments in upland east Otago, New Zealand, where the present study was carried out. After seven years growth the catchment planted in *Pinus radiata* was showing up to 50% reduction in peak flow compared with the *Chionochloa rigida* grassland control catchment. Flow duration curve analysis showed that less water was being released to low flow from the planted catchment. In a study near Dunedin, Smith (1987) compared hydrologic regimes of exotic pasture and exotic pine forest. The pasture catchment consistently yielded greater quantities of water throughout all stages of the flow regime. In the Glendhu experiment evaporation differences between tussock and pine are believed to be the underlying cause for the reduction in water yield following afforestation (Murray *et al.*, 1990). Campbell (1987) believed transpiration rates of tussock were similar to forest, while Fahey and Watson (1991) demonstrated the increased interception loss from the pine.

While water yield is a quick and simple variable to characterise differences in the hydrologic regimes of different vegetation treatments, more detailed information can be gained by investigating peak flow and low flow discharges and quickflow ratios, as has been done in the Glendhu experiment by Fahey and Watson (1991).

2.1.2 Soil moisture changes

Flow regimes are only one part of the water balance that may be altered due to a vegetation change. Soil water status is another useful tool for determining the hydrologic effects of different vegetation covers, but to date no specific work has been done on soil water regimes at Glendhu. Published comparisons of soil moisture contrasts between forested sites and grasslands are scarce, but the little information available points to dryer soil profiles under forest.

Pyatt and Smith (1983) compared sitka spruce with the natural grass cover in southern Scotland. In both years of the study, results showed a similar pattern. Under forest, bore holes seldom had free standing water, and during the summer matric potentials in some soils fell below $-800\,mb$. In the unforested grasslands, bore holes not penetrating the iron pan held water continuously for the 2 year period, but deeper bore holes behaved similarly to those of the forest. During the summer no pronounced drying occurred and matric potentials never fell below $-105\,mb$ under grass. Pyatt and Smith (1983) attributed a fall in the water table and generally dryer conditions under forest to an increased evaporation to rainfall ratio.

In another British study King *et al.* (1986) looked at four vegetation covers on two different soils. The study ran for two growing seasons with two forest covers, sitka spruce and lodgepole pine, being compared with two native vegetation covers, *Molinia spp.* grasslands on a peaty gley soil and *Calluna spp.* heath on a deep peat soil. The water table was lower at the forest sites than at the native grass sites, the difference being greatest in the summer. Matric potentials fell below $-400\,mb$ in the summer under trees, but did not go below $-50\,mb$ under native grassland, and unsaturated conditions prevailed longer under trees than under grass. In the deep peat soil the native heath vegetation was examined in a plot that was undisturbed and in one that had been ploughed. *Calluna spp.* (undisturbed), *Calluna spp.* (ploughed), sitka spruce, and lodgepole pine formed a progression from wettest to driest soil conditions. Enhanced interception of rainfall is considered the cause.

Pyatt and Craven (1979) compared forest, heathland, and grassland soil moisture regimes with soils that would appear from the description given to be similar to those found at the Glendhu catchments. Waterlogging occurred at the surface for most of the year in the heathland soils, but did not occur at all under the forest. There was only a small amount of drying in the heathland sites during the summer, which Pyatt and Craven (1979) attributed to the low transpiration rates of the heather. In the forested sites there were long drying periods with matric potentials falling below $-800\,mb$ for several weeks at a time. These results may be indicative of likely soil water differences at Glendhu because heather appears to have similar evaporative characteristics (Miranda *et al.,* 1984) to snow tussock (Campbell, 1987).

2.2 Hillslope hydrology

Hillslope hydrology deals with the partition of precipitation between overland flow and subsurface flow, and the consequent attenuation and delays as water moves through hillslopes to the channel system. Many catchment studies have measured inputs and outputs of the system, without attempting to understand the distribution and behaviour of water in the soil on hillslopes, so that the processes may be more fully understood (Helvey *et al.,* 1972).

Soil water behaviour on level ground may be dominated by the properties of the soil, but on uneven and steep ground soil water will also depend on topography (Ward and Robinson, 1990). In an artificial slope of homogeneous soil Hewlett and Hibbert (1963) recorded discharge from the base of the slope, after a period of initial saturation, for more than two months, and concluded that "unsaturated flow in mountain soils is both an important and immediate cause of sustained baseflow in mountain streams" (Hewlett and Hibbert, 1963:1086). Throughout this experiment soil water content increased downslope. In New Zealand, van't Woudt (1955) showed moisture in a volcanic ash soil increasing gradually from the top to the foot of the slope. A similar downslope increase in moisture was found by Stoeckler and Curtis (1960), with the magnitude dependent on aspect.

Helvey *et al.* (1972) measured soil moisture on forested slopes in western North Carolina in order to develop equations for predicting soil moisture contents of watersheds. The distance above the stream channel only seemed important for the lower 25% of the slope, but seasonal changes in soil moisture were found to be greatest upslope at all depths.

Saturated and unsaturated conditions may occur simultaneously within a slope (Buttle and Sami, 1992). The extent of the saturated zone at the base of the slope and the way it behaves during precipitation is important when considering storm runoff generation (Ward and Robinson, 1990). Weyman (1973) identified a typical sequence of events in a slope during a storm event. In the initial situation the soil water state of the slope was near complete gravity drainage. Soil water potential within the soil matrix decreased upslope approximately offsetting the increase in gravitational potential. There was some saturated lateral flow near the base of the slope. With the onset of rain, potentials at the soil surface increased giving vertical water movement, while saturated lateral flow continued at the base of the slope. As rain continued, vertical flow increased the size of the saturated wedge at the base of the slope. After rain, drainage from the upper horizons to lower horizons continued and there was some further expansion of the saturated wedge.

During rainless periods, streams are often supplied by moisture migrating downslope under conditions of unsaturated flow. The result is a theoretical gradient of increasing moisture content downslope that provides a primed zone along the channel edge for quick release during storm events (Helvey *et al.*, 1972). This concept is termed 'variable source area' and was suggested by Hewlett and Hibbert (1967) and has since been modified to allow for convergence in areas disjunct from the stream channel (Kirkby and Chorley, 1967). Three different situations have been proposed by Kirkby and Chorley (1967) where flow convergence may occur, leading to possible 'saturated overland flow':

- slope concavities in plan which have subsurface flow rates that exceed the transmission capacity of the soil, causing water to flow from the soil surface in areas in the middle of the concavity where convergence is greatest;

- breaks in slope causing concavity in section in which there is a saturated zone in the profile throughout the section and the material is homogeneous, the saturated subsurface flow will be proportional to the slope; and

- areas of thin soil in a slope may not have the ability to transmit all water flowing downslope.

2.3 Hydrology of headwater peat wetlands

Leslie and McGlone (1973) regarded the Taieri uplands as being a relic landscape largely shaped by periglacial activity during the late Otiran glaciation. Drainageways have been aggraded and infilled to form wetlands between broad interfluves. The wetlands that form in the infilled gullies are peculiar to the topography of these uplands.

The general consensus until recently has been that wetlands are hydrologically significant, as they are believed to both attenuate floods and to sustain baseflows during periods of low precipitation (Roulet 1990a). Davoren (1978) viewed peatlands as sponges and has cited examples from around the world of flood-peak problems, erosion, and chemical characteristic changes, that have occurred after the removal of peatlands. But specifically within New Zealand, Davoren (1978) mentioned that higher flood peaks and nitrate levels have been found after peatland reclamation and believes that the conservation of mountain top blanket bogs in Southland and Otago is important.

Roulet (1990a) believed that there is no characteristic hydrology specific to peat wetlands and the extent to which wetlands contribute to low flow depends on the ability of the wetland to store water and whether the wetland receives continuous flow. The discharge of groundwater in headwater environments can be an important factor in the maintenance of stream discharge (Freeze, 1972). Wetlands often form as a result of persistent saturation in discharge zones (Roulet, 1990b) and wetlands such as this may contribute water to low flow all year (Roulet, 1990a).

Pearce *et al.* (1984) determined that the Glendhu catchments had sustained flow rates, between episodes of storm runoff, that were unusually high, and that 90% of the flow duration for the area occurs during the slow recession. This was attributed to drainage from regolith storage which was defined as shallow, unconfined groundwater, but the upland wetlands were not identified specifically as the source. Runoff mechanisms inferred in the study of Bonell *et al.* (1990) identified the wetlands at Glendhu as important because of the significant surface storage which had to be exceeded before 'new' rain water became a significant contributor to stream discharge. Translatory flow is the process of displacement of 'old' rainwater stored in the soil into the channels by 'new' rain water as described by Hewlett and Hibbert (1967). Both quickflow and baseflow discharges from the catchment were found to have a high 'old' water content.

At Glendhu casual observations have revealed that water tables in gully wetlands appear to be near or at the surface throughout the year, but there is no knowledge as to the role of the regional ground water system. With consideration of the limited storage of the wetlands, if wetland water is the main contributor to low flow, water tables should fall rapidly during recession periods. The wetlands in the Glendhu region may not be the cause of sustained low flows, but the slow recession curve characteristics of the area may be supplied by water stored in the adjacent regolith or rock, and the wetlands could be a consequence.

3

Field Area and Methods

The present study looked at three aspects of the hydrology of the Glendhu region. The first compared soil water regimes under *Chionochloa rigida* and *Pinus radiata*; the second investigated soil water regimes in relation to different topographic positions; and the third aspect was a preliminary investigation of some of the hydrological characteristics of a wetland in the Glendhu region. The main questions for this study were:

- Do soils dry more under the pine canopy than under the tussock grassland during summer drying periods?
- Is there a difference in the direction and magnitude of the moisture flux during drying periods under pine and tussock?
- How does the seasonal cycle of water status differ between tussock and pine?
- During very wet periods is the soil status under pine and tussock similar?
- Does topography, in particular slope position and slope form, influence the soil water status and the likelihood of runoff generation from saturated overland flow?
- Does the water table of a gully wetland fall during flow recessions? and
- What volume of water is released or stored if water table changes do occur in the gully wetland?

The Glendhu experimental landuse catchments in eastern Otago were chosen as the location for this study (Figure 1.1). In October 1993, field installation commenced with six tensiometer nests and six neutron probe access tubes being installed in both the *Pinus radiata* and *Chionochloa rigida* catchments. In November 1993 five tensiometer nests were installed in a headwall convergence zone and five observation wells in the adjacent peat wetland.

Data were collected between October 1993 and May 1994, at intervals dependent on weather conditions. There were few observations during wet periods and not all instruments were read on every visit to the catchments.

3.1 Glendhu field sites

3.1.1 Location and description

In July 1979, a paired catchment experiment was set up at the former Glendhu State Forest (the study area is presently owned by Rayonier Ltd.), on the southern end of the Lammerlaw Range in the east Otago uplands. The paired catchments are part of the Upper Waipori river catchment and lie approximately 70 km west of Dunedin city. The catchment experiment was established to study the hydrological impacts of converting lightly grazed *Chionochloa rigida* grassland to *Pinus radiata,* with one catchment being retained in its original state as a control. The two catchments are named GH1 (207 ha) and GH2 (310 ha) with the former, the control, remaining in tussock (Figure 1.1).

The catchments are adjacent and have north facing aspects. The topography is steep to rolling and altitudes range from 460 m to 670 m a.s.l. The dendritic drainage pattern is usually characterised by first order streams less than 400 m in length which rise in amphitheatre like heads (O'Loughlin *et al.,* 1984). In the upper reaches of the catchments, bogs and wetlands are common in depressions between interfluves and occupy 10% of the catchments (Fahey and Watson, 1991).

The underlying geology of the area is an uplifted block of quartz-feldspathic schists which belongs to the Haast group (McKellar, 1966). There has not been a soil survey of the Glendhu catchments, but the survey of the Waipori farm settlement (Hewitt, 1982) covered areas adjacent to the study sites, and after personal inspection of the area, Hewitt (pers. comm.)[1] confirms that the soil patterns are similar to the Waipori farm settlement survey. Hewitt (1982) distinguished areas of weakly and strongly weathered basement schist, while schist loess mantles much of the catchment, but is thinnest on ridge crests and west facing slopes. This is consistent with the variable depths observed in road cuttings at Glendhu.

Hewitt (1982) identified a broad topographic pattern for soil in the region. Soils vary in drainage, slope, and parent material from ridge crest to valley bottom. On slopes

[1] Personal communication with Dr. Alan E. Hewitt, Landcare Research, Dunedin.

of up to 30^o Waipori silt loams (loess $< 45\,cm$ thick), or Mahinerangi hill soils (loess $> 45\,cm$ thick) occur on the broad crested interfluves and steep convex slopes, with a mottled subsoil indicating imperfect drainage. On slopes greater than 28^o Nardoo steepland soils are shallow, stony, silt loams, less than $0.2\,m$ deep, and are well drained with no apparent mottling. These merge into the Pioneer silt loams which are poorly drained, with deep gleying on the lower toe slopes. The formations in the wetlands at this altitude are Bungtown peats.

The catchments sit in the lee of the Southern Alps and in the path of the prevailing westerly weather systems, with strong dry northwesterly winds often preceding cold fronts (Fahey and Watson, 1991). The nearest climatological station is at Lake Mahinerangi ($400\,m$ a.s.l.), $20\,km$ to the east of the catchments. Mean temperature is 8.6^oC at this station and varies between 12.7°C and 3.6^oC for January and July respectively (New Zealand Meteorological Service, 1983). While the average rainfall at Lake Mahinerangi is $960\,mm$, Pearce *et al.* (1984) estimated mean annual precipitation for the Glendhu catchments to be $1305\,mm$ for the period 1980–1982, with monthly precipitation varying from 25 to $264\,mm$. Snowfall was also estimated to contribute less than 10% to annual precipitation.

The natural vegetation associations of the two catchments were described by O'Loughlin *et al.* (1984). Narrow-leaved snow tussock (*Chionochloa rigida*), and the associated browntop (*Agrostis capillaris*) and sweet vernal (*Anthoxanthum odoratum*) form the dominant ground cover, while red tussock (*Chionochloa rubra*), *Juncus spp.*, and *Sphagnum spp.* are the main components of the poorly drained valley bottom peats.

During 1981 the slopes of GH2 were ripped by a bulldozer to a depth of approximately $60\,cm$ at $3.5\,m$ intervals, and *Pinus radiata* seedlings were planted at 1250 stems/ha over $207\,ha$ (67%) of the catchment in June 1982. The valley bottoms and bogs were not planted (Figure 1.1). At present there is still an understorey tussock canopy in many areas of the planted catchment as canopy closure is not complete. The pines at present average approximately $5.7\,m$ in height, and large gaps are opening in the canopy as a result of high wind throw. The tussock catchment (GH1) is lightly grazed, with stocking rates never exceeding one sheep/ha.

3.2 Field installations

Three sites were established in each catchment to represent upper, middle and lower slope positions on a interfluve, the location of the pine catchment sites being marked in Figure 1.1. Tussock interfluve sites were positioned in a subcatchment of GH1, chosen for more detailed investigation, and five sites were also established in the adjacent wetland and five sites on the wetland headwall (Figure 3.1). Figure 3.2 is a photograph of the wetland.

The tussock subcatchment was chosen for comparison of soil water regimes in relation to topography. Figure 3.3a shows the longitudinal profile of the tussock interfluve which has a similar convex shape to the headwall slope (Figure 3.3b), with gradient increasing downslope to the toe. Both the tussock lower, and headwall number 5, sites sit above a steep break in slope as the profile drops to the wetland.

3.2.1 Neutron probe access tubes

Twelve 44.5 *mm* o.d., 17 gauge aluminium access tubes were installed by Landcare Research. Two tubes were installed at each of the interfluve sites, approximately 3.5 *m* apart, to a depth of 100 *cm* or to the surface of the underlying schist. The left tube of the tussock middle site is the only short tube and was inserted to a depth of 80 *cm*.

Each tube was driven into the soil in 10 *cm* increments using a sledgehammer. To prevent deformation the top of the tube was protected by a nylon cap. The soil was removed from the bottom of the tube after each 10 *cm* increment, using a screw auger, taking care not to auger past the bottom of the tube. After installation, 100 *mm* of tube was left exposed at the surface for the probe housing to rest on. The area around each tube was covered by base boards during installation, to reduce trampling and compaction.

3.2.2 Tensiometers

Two nests of tensiometers were installed at each interfluve site, one nest to the true left of each neutron probe access tube at all tussock and pine interfluve sites, and five nests (with no replication) were installed in the headwall of the GH1 subcatchment wetland. Tensiometers were of the Loktronic brand, and have a coloured PVC tube of appropriate length attached to a porous cup. The top of the tube has a clear perspex section to allow the water level to be read, and a rubber septum into which the needle of the portable Loktronic pressure meter is inserted, caps the tensiometer.

Each tensiometer nest consisted of four tensiometers with the centre of the porous cup inserted 10, 30, 60, and 90 *cm* below the surface. To install the tensiometer a 25 *mm* diameter hole was bored with a screw auger to the required depth. This hole has a diameter 4 *mm* greater than the tensiometer porous cup, to allow a slurry of fine loess and water to be poured down the hole in order to seal the tensiometer in place. This

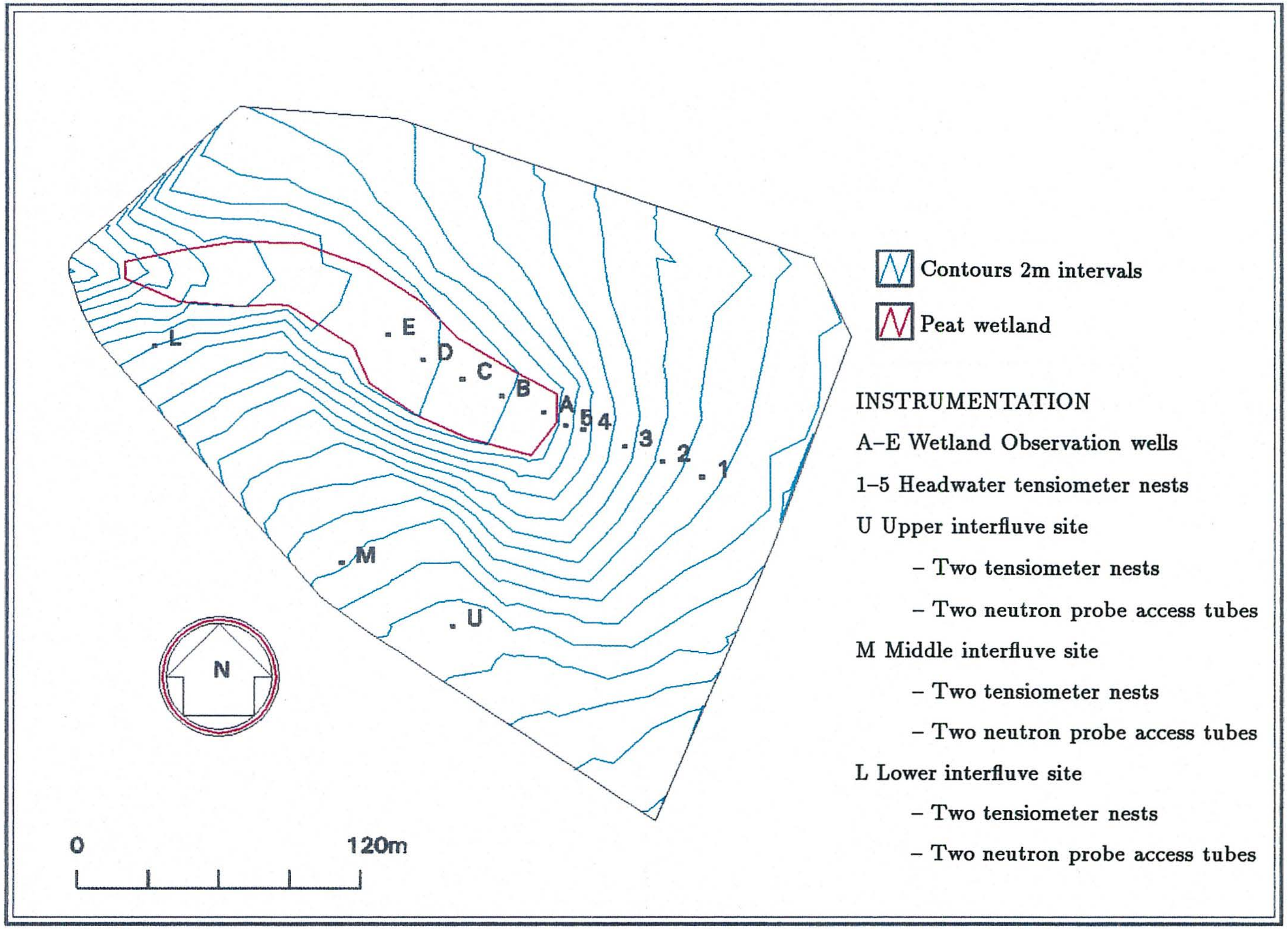

FIGURE 3.1: The tussock (GH1) subcatchment with upper, middle, and lower sites, headwall tensiometers, and observation well installation sites marked.

FIGURE 3.2: The tussock (GH1) subcatchment wetland.

prevents water running down the sides of the tensiometer from the surface, and fills the gap around the porous cup created by auguring. Tensiometers were filled to 1 cm below the top, using water that had been boiled for several minutes to remove air.

The middle site on the GH1 interfluve does not have a 90 cm tensiometer in the left nest, as the depth to schist was too shallow.

3.2.3 Observation wells

Wetland installations comprised a single water table observation well at each of the five sites. These were 2 m long, 27.5 mm i.d. PVC tubing, that was capped at the bottom end to prevent the peat entering the tube on installation and had 4 mm holes drilled at 30 mm intervals down one side. The tubes were installed by either first boring a 40 mm diameter hole with a screw auger, or by pushing them directly in to the bog if no hard lenses were encountered. Between 10 and 30 cm of the tube was left exposed at the surface depending on the depth of peat. The tubes were capped to prevent rainwater entry between measurements.

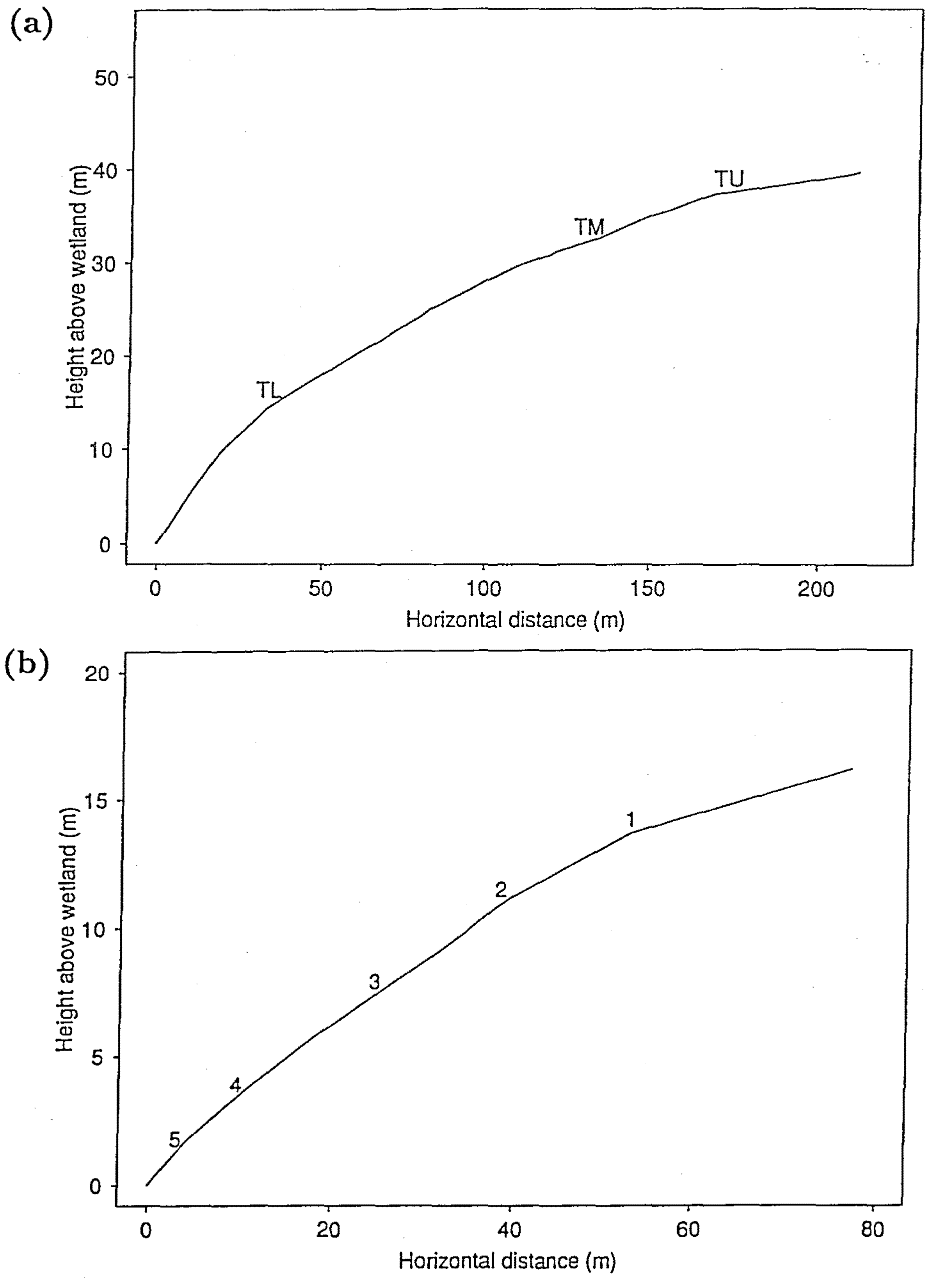

FIGURE 3.3: Subcatchment slope profiles: (a) interfluve running through tussock upper (TU), tussock middle (TM), and tussock lower (TL) sites (vertical exaggeration 4x); (b) headwall running through tensiometer nests 1–5 (vertical exaggeration 4x).

3.3 Data collection procedures

3.3.1 Soil water regimes

Soil moisture was measured using a Troxler 3330 series neutron probe. Counts of thermalised neutrons were recorded at 10 cm increments over 30 second intervals, and these were recorded manually. Part way through the field season the first probe malfunctioned, and a second Troxler 3330 series probe was used.

The first Troxler 3330 series neutron probe had been calibrated in a loess over schist soil by Eyles (1987). The appropriate calibrations were selected for the different horizons at Glendhu. Water tank testing of the second neutron probe suggested that the calibration for the original neutron probe would also be suitable. The calibrations of Eyles (1987) which were used are:

$$\begin{array}{ll} \theta = +0.10 + 0.78 \times R & 0\text{--}10\,cm \\ \theta = +0.01 + 0.81 \times R & 10\text{--}20\,cm \\ \theta = -0.10 + 1.00 \times R & > 20\,\mathrm{cm} \end{array}$$

where θ is the water content expressed as volume fraction, and R is the ratio of the measured count rate to the count rate in a standard absorber. A standard count was obtained in a water tank. As the probe has not been specifically calibrated for the soils at Glendhu, volumetric water contents can only be used for comparison between treatments. Eyles (1987) found that the slope of the calibration did not differ significantly between different soils, but the intercept does. Therefore differences in volumetric water storage can be assumed to be representative, although because of the likely error in intercept, volumetric contents are less certain.

A datum date was selected a few days after significant rainfall. The soil water storage at this date was considered to represent the maximum storage within the profile after excess water had runoff or drained. This date was used for all tubes. Profiles were divided into two sections, 0–30 cm and 30–100 cm. Average differences in the datum date water content between tussock and forest, and different topographic positions, were compared for the two layers and the whole profile. Differences in water content were also compared for other dates during the study period. Water storage at each date of observation was also subtracted from water storage at the datum date. Values were expressed in mm depth for easy comparison with rainfall and referred to as storage opportunity. If storage on the date of observation was greater than that of the datum date, storage opportunity is 0 mm as the excess water was considered to be only temporarily stored in the profile. Storage opportunity was calculated for both layers, and storage opportunity for the entire profile is the sum of these layers. Averages were calculated for appropriate tubes for various storage opportunities comparisons.

The Loktronic tensiometers were read using a portable, battery powered, Loktronic pressure meter. A syringe needle attached to the meter was inserted through the rubber septum of the tensiometer and the reading was taken once the readout stopped fluctuating. Insertion of the needle disturbs the equilibrium pressure within the tensiometer and if tensions are low equilibrium may take some time to re-establish (Cresswell, 1993). The height of water in the tensiometer tube was measured by inspection through the clear plastic top, and recorded at every reading. Water levels were topped up, after reading, if they fell more than 2.5 *cm* below the top of the tensiometer tube.

Matric potentials at the porous cup were calculated assuming that the pressure applied by 1 *cm* of water = 98.06 N/m^2. The head of water (*cm*) above the centre of porous cup was calculated from the water level measurements taken at each recording. Therefore:

$$matric\ potential\ (mb) = meter\ pressure\ (mb) + (\ head\ of\ water\ (cm) \times 0.9806)$$

For each tensiometer nest the datum level for total potential calculation was taken as the top of the 10 *cm* tensiometer tube. The total potential was then calculated by subtracting the distance (*cm*) between the datum and the porous cup from the matric potential calculated for that tensiometer.

When averages were calculated between nests and between sites for the various depths, tensiometers that had run dry because of deterioration of the ceramic cup or seal, or because the water had been extracted due to potentials below $-800\ mb$, were excluded from the average calculation. In the last situation average matric potentials may be lower than actually calculated, though information is not available to confirm this. This situation occurred on several occasions for some tensiometers at the 10 *cm*, and on occasions at the 30 *cm* depths.

Water levels were measured at the observation wells by lowering a weighted steel tape measure with two insulated wires 1 *cm* apart attached to the end. These wires had bare ends and were connected to a multimeter, and resistance decreased abruptly when the wires entered water. Depth to water from the top of the well tube was recorded. Expansion and contraction of the bog was also recorded between mid January and the conclusion of the experiment by measuring the distance from the top of the well tube to a small piece of plywood laid on the bog surface.

Rainfall and catchment discharge data from a wier and rain gauge located at the bottom of each catchment was supplied by Landcare Research, Christchurch.

3.3.2 Soil physical property determination

Pits were dug near each of the interfluve sites in both the tussock and pine catchments, and at several locations adjacent to the headwall tensiometer nests. The horizons were measured and described. Particle size analysis and bulk density determinations were carried out on samples of the main horizons. Particle size analysis used the hydrometer method with air dried soils that have passed through a 1 mm sieve. Bulk density calculation was carried out using the core method. These procedures were conducted as described in Klute (1986).

Six 213 mm diameter cores of the wetland peat material were taken at random locations near the observation wells. These were 300 mm deep and were extracted by placing a sharpened PVC pipe at the surface and working it into the peat using a long knife to cut around the core. The base of the core was trimmed on removal from the bog.

In the laboratory the core was sealed with PVC at the base and saturated with water. At 100 mm intervals down the core, the drainable porosity was estimated by draining the core through a 4 mm hole and dividing the volume of water by the volume of the section of the core drained. After draining, four of the six cores were oven dried at 105°C for 24 hours. After drying, total porosity was estimated by calculating the total water lost since saturation and dividing this by the volume of the core, while bulk density was calculated by dividing the resulting mass by the known volume.

A survey of the peat depth of the GH1 subcatchment wetland was carried out. Transects were run across the wetland at 15 m intervals, and depth of peat determined by probing with a 10 mm steel rod at 5 m intervals along these transects.

3.4 Data Analysis

Means and standard errors were calculated for the different horizons and vegetation cover bulk density data. Mann-Whitney tests where used to determine differences between the data sets because of the non-parametric nature of the data. A table of PSA results was constructed, with means and standard errors for the different horizons.

Graphical analysis was used to investigate soil water regimes. Averages of matric and total potentials, as well as storage opportunities, were plotted against time in various forms to compare vegetation and topographic relationships. Variations in soil water storage were also considered in relation to vegetation and topographic effects. Wetland well fluctuations were also graphically interpreted.

4

Results and Discussion

4.1 Vegetation effects

4.1.1 Soil physical characteristics

Soil horizons

The soil profiles at each of the interfluve sites in both catchments are described in Table 4.1. Horizon depths are similar except for the tussock middle site which is a Waipori hill soil, as opposed to a Mahinerangi silt loam. The A/B horizon is a result of worm mixing, and at both catchments macroporosity in the upper layer may be high because of worm activity. There is also a clear structural discontinuity between A and B horizons in both catchments, though this was less pronounced in the pine profiles examined.

Gleying was often present near the A and B horizon interface in the tussock catchment, but lower numbers of mottles were observed at the pine sites, and those observed were generally not as intense. Peds found in different inspection pits along the tussock interfluve often had an iron veneer along the faces. The presence of gleying indicates long periods of anaerobic conditions (Fitzpatrick, 1980), and these sections of the profile must therefore experience saturation for a large part of the year. The extra intensity of mottling in the tussock soil profile may indicate wetter conditions when compared with the pine, though it is difficult to know whether the planting of pines could have removed or reduced the intensity of mottling in the profile over this short period of time. The abundance of mosses on the surface between tussocks also indicates that the surface remains moist for most of the time. In the pine catchment there was little *Sphagnum spp.* cover at the surface.

TABLE 4.1: Soil profile description of *Pinus radiata* and tussock interfluve sites (Colour codes follow Munsell charts).

Horizon	Depth (cm)	Colour	Description
Tussock Upper – Mahinerangi silt loam			
Om	4–0		Patchy sphagnum moss
A	0–16	10YR 4/1	Some mottles lower layers, schist chips
A/B	16–29		Intensely mottled (5YR 5/8)
B	29 –80+	10YR 5/4	
Tussock Middle – Waipori hill soil			
Om	5–0		Sphagnum moss layer
A	0–19	7.5YR 3/2	Dense root fabric 0–5 cm
A/B	19–29		Mottled (2.5YR 5/8)
B	29–45	10YR 5/4	
B/C	45–		Strongly weathered schist
Tussock Lower – Mahinerangi silt loam			
Om	4–0		Sparse sphagnum moss cover
A	0–21	7.5YR 3/2	Dense root fabric 0–5 cm
A/B	21–31		Little mottling
B	31–80+	10YR 6/6	Low macroporosity, lower mottles
Pine Upper – Mahinerangi silt loam			
Om	6–0		Litter layer
A	0–15	10YR 4/2	Dense fine pine roots 0–4 cm
A/B	15–25		Some mottling (5YR 5/8)
B	25–100+	10YR 5/4	Few mottles present
Pine Middle – Mahinerangi silt loam			
Om	5–0		Litter layer
A	0–19	7.5YR 3/2	Dense root fabric, strong nutty structure, and no mottling
A/B	19–25		
B	25–100+	10YR 5/4	Some mottles upper B (5YR 5/5)
Pine Lower – Mahinerangi silt loam			
Om	3–0		Litter, with some moss present
A	0–19	10YR 4/2	Dense root fabric and strong nutty structure
A/B	19–31		
B	31–100+	10YR 5/4	Low macroporosity, many lower mottles

Bulk density and porosity

Bulk density at tussock and pine sites for the A and B horizons are compared in Table 4.2. Because of the low sample size for pine, the power of a statistical test for difference in population median will not be great. The A and B horizon comparisons do not indicate that differences in the bulk density have developed between vegetation covers at this stage, though the tussock samples tend to have higher bulk densities.

If a particle density for a mineral soil such as that at Glendhu is assumed, a total porosity may be calculated, and therefore the consequence of a lower dry soil bulk density may be quantified. If the average dry soil bulk density of the pine is lower than that of the tussock, the theoretical water storage at saturation will be greater. The mean porosity between the two vegetation covers must be considered to be the same, as differences in dry soil bulk density are not significant. At Glendhu, a pronounced subangular block structure which was observed at locations under the pine canopy, was not as obvious at tussock observation pits, indicating that structural changes may be occurring under the pines. The development of this type of soil structure has been attributed to frequent wetting and drying of the soil peds (Fitzpatrick, 1980).

Soil structure has a large influence on the pore size range of a soil (McLaren and Cameron, 1990). What may be occurring at Glendhu as a result of afforestation is a change in the distribution of different sized pores within the soil profile. Jackson (1973, 1974) found in a study of pumice soil near Rotorua, New Zealand that differences in the soil structure under forest and pasture were largely confined to the upper A horizon. The topsoil under native forest contained a larger number of large pores that would drain at pressures less than $-50\ mb$.

In a long term study of the effects of forest on the physical properties of pumice soil, Jackson (1980) found that after 6 years growth of *Pinus radiata* that was planted at the time of the Jackson (1973) study, differences in the physical characteristics of the soil were quite marked. The percentage of large pores, saturated hydraulic conductivity, and infiltration rates, were all greater under pine when compared with permanent pasture. Changes after six years also included the development of a fine crumb structured soil in the top layers of the original massive or platy structured topsoil. The development of better structure in the root zone under spruce has also been noted by Pyatt and Craven (1979) in both mineral and peat soils.

TABLE 4.2: Comparison of dry soil bulk density (ρ_b) between tussock and pine cover.

Horizon	Cover	Mean (ρ_b) gcm^{-3}	SE (ρ_b) gcm^{-3}	Mann-Whitney P-value
A	Tussock	0.94	0.05	0.10
	Pine	0.79	0.04	
B	Tussock	1.34	0.03	0.48
	Pine	1.29	0.07	

Particle size analysis

A particle size analysis (PSA) of soils from the tussock catchment should be representative of particle size distributions found in both tussock and pine soils, as changes in vegetation cover are unlikely to affect this soil property over a short time span. Table 4.3 contains results from PSA for five A horizon and four B horizon samples taken from the tussock subcatchment.

There is considerable variation in particle size distribution within each horizon, with the B showing higher sand and clay contents. The B horizon often contains clasts of highly weathered schist, which will increase the proportion of larger sized particles, although the method used for this analysis required samples to be put through a 1 mm sieve before processing. One of the B samples contained large numbers of clasts. Of the two samples from the lower A, one is gleyed and this contained the lowest sand and the highest clay content of all the A horizon samples.

The sample was limited and higher variation is to be expected, although the profiles at Glendhu are highly variable, with soils being developed on many combinations of *in situ* weathered schist, colluvium and schist loess (Hewitt, 1982). Large differences between the particle size distribution have not been found, as would be expected because the A horizon has developed from B material. The proportions of sand, silt and clay are similar to those described by Leslie and McGlone (1973) for secondary loess colluvium in the region.

4.1.2 Rainfall and catchment discharge

The period of data collection (September 1993 – May 1994) was wetter than normal, with several large storms and many long periods of low intensity rainfall. Monthly

TABLE 4.3: Particle size analysis results from GH1.

Horizon	Depth (cm)	% Sand	% Silt	% Clay
A	15	31.1	59.5	9.4
	15	22.2	65.2	12.5
	15	41.3	52.8	5.8
	20	36.8	55.8	7.3
	33	14.8	64.2	20.9
Mean		29.2	59.5	11.2
SE		4.8	2.3	2.6
B	45	42.6	43.6	13.7
	75	16.6	64.8	18.5
	85	66.7	22.3	10.9
	85	15.3	69.3	15.2
Mean		35.3	50.0	14.6
SE		12.2	10.8	1.5

rainfall at the tussock and pine catchment weirs is shown in Table 4.4, and differences between the catchments are small. December 1993 was the wettest month during the study period, with April 1994 being the driest.

Figure 4.1 provides a comparison of the discharge from the two catchments during the period of data collection. The study by Fahey and Watson (1991) found both peak discharge and recession flows from the pine catchment at Glendhu were lower than from the tussock after 7 years of pine growth, and this trend has continued to date. The streamflow recessions of the two catchments are in phase and three main recession

TABLE 4.4: Monthly rainfall at the tussock (GH1) and pine (GH2) catchment weirs between September 1993 and May 1994.

	Rainfall (mm)								
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
GH1	119.4	104.6	90.2	241.6	161.8	88.4	187.4	67.6	110.0
GH2	125.6	105.6	98.0	249.8	163.0	90.0	199.6	72.6	97.8

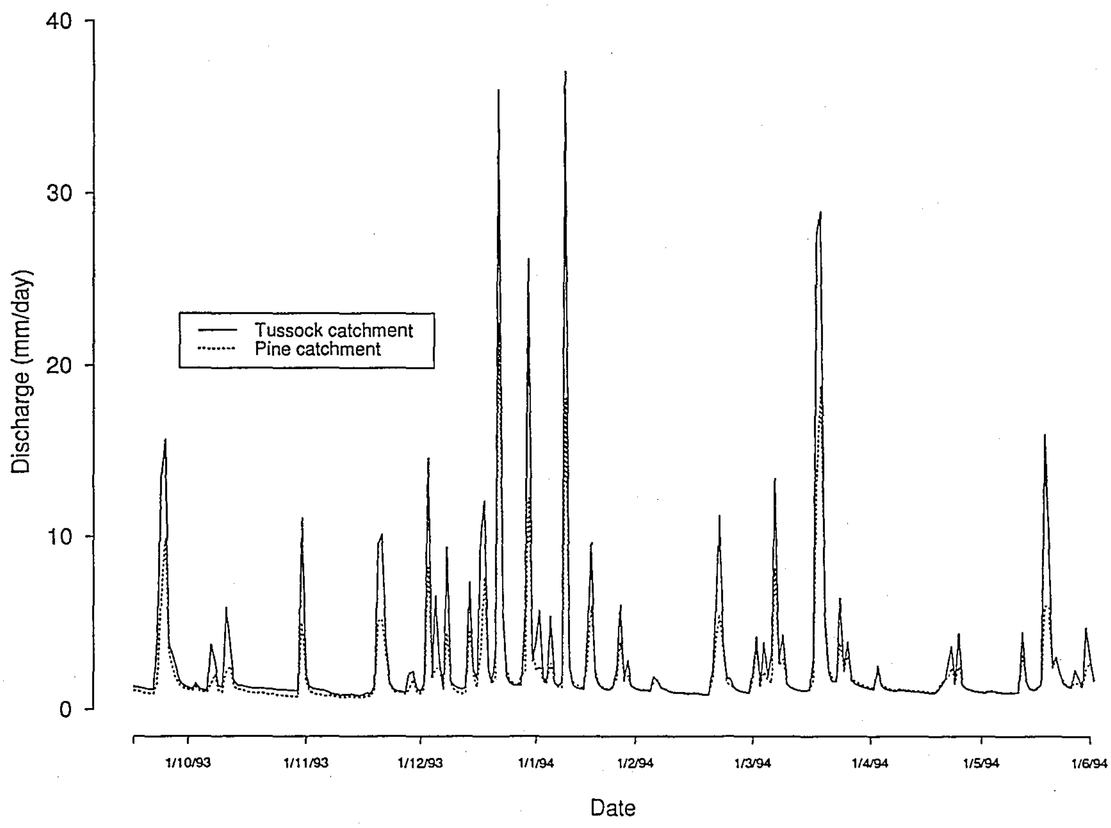

FIGURE 4.1: Discharge from the tussock and pine catchments.

periods are evident: the first in October and November 1993, though this was disrupted by a 35 mm rainfall; the second in late January and February 1994, and the third in April and early May 1994.

4.1.3 Matric potential

Even with the unusually wet summer, moisture deficits developed in both catchments. Variation between tensiometer nests at each interfluve site was high, as was variation between sites, although averages appear reasonably stable.

Figures 4.2b and 4.3b show averaged[1] matric potentials from tensiometer data through time for the tussock and pine interfluve sites, together with rainfall and stream discharge (Figures 4.2a and 4.3a). The streamflow recessions of late October and early November 1993, and February 1994 coincide with significant lowering of the matric potentials in the pine catchment and to a lesser extent in the tussock catchment. There was also a dry period during April 1994, but this did not produce large soil moisture

[1]A full listing of matric potentials from the interfluve tensiometer nests is given in Appendix A

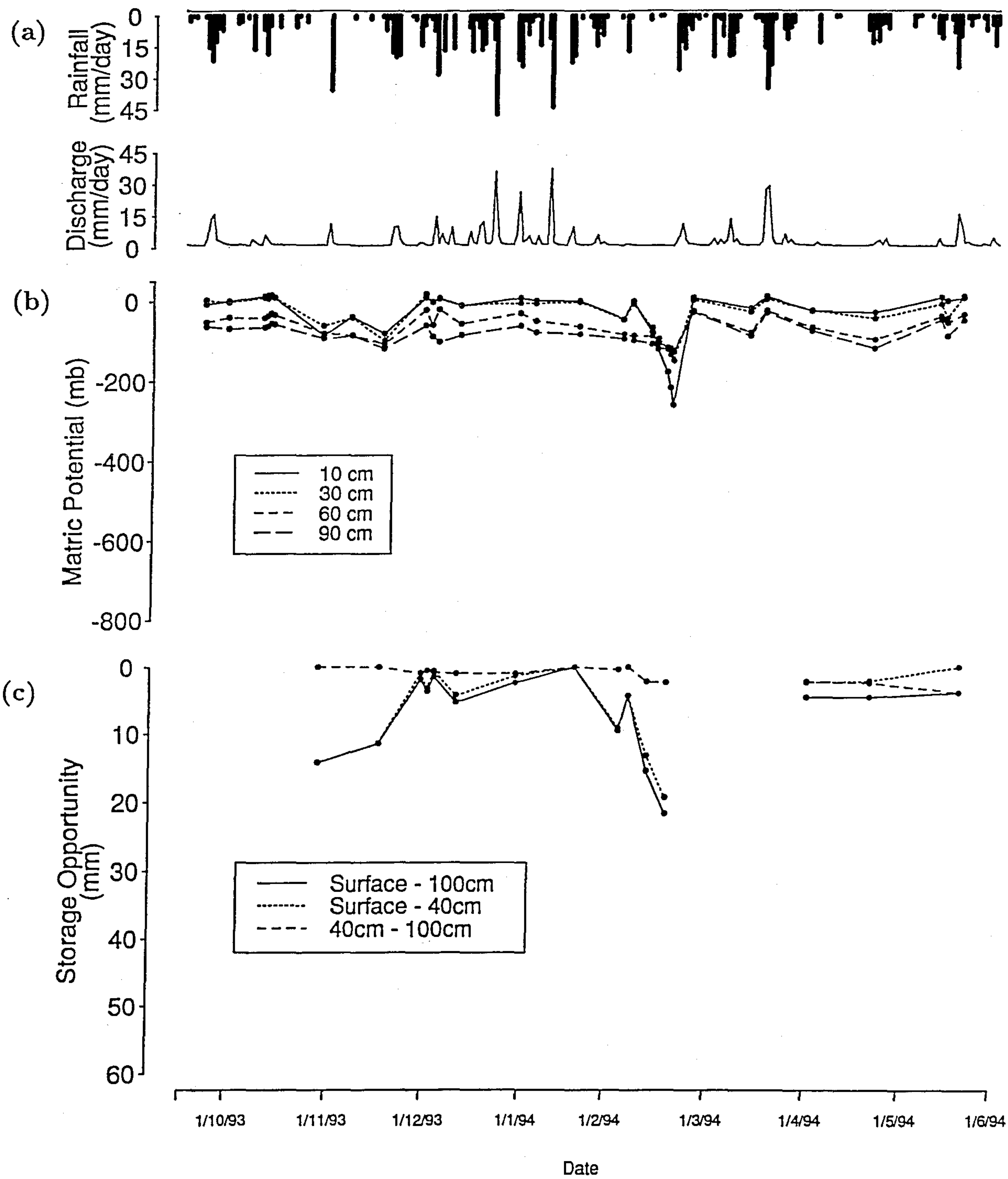

FIGURE 4.2: Average soil water regime at the tussock interfluve sites during the study period: (a) catchment rainfall and runoff; (b) matric potential; and (c) storage opportunity.

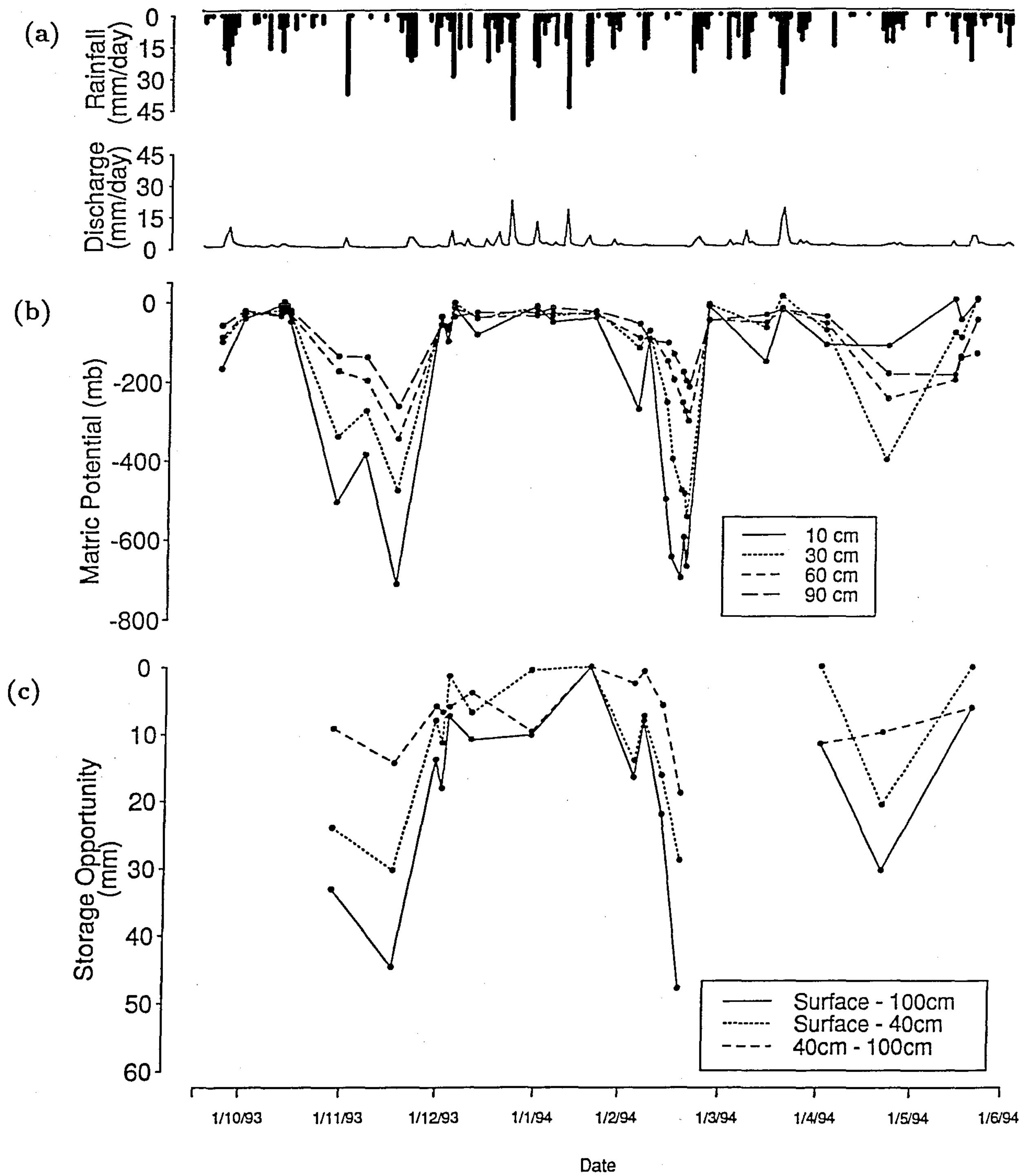

FIGURE 4.3: Average soil water regime at the pine interfluve sites during the study period: (a) catchment rainfall and runoff; (b) matric potential; and (c) storage opportunity.

changes in the tussock catchment.

Little soil drying occurred under tussock cover during the summer months (Figure 4.2b). The greatest decrease in matric potentials occurred in the 10 *cm* layer in February, with matric potentials falling close to $-300\ mb$. At 90 *cm* depth there was little variation during the summer.

There was greater drying below the pine canopy, with the average matric potential falling below $-700\ mb$ at 10 *cm* depth at the peak of the two major drying periods. At 90 *cm* depth, matric potentials fell from $-16\ mb$ to $-264\ mb$ during the spring drying event.

Saturation does not occur at any stage under the forest as revealed by the averaged matric potentials which remained positive. In the tussock catchment, there is some evidence for a perched water table near the base of the A horizon throughout much of the study period with matric potentials at the 60 and 90 *cm* depths being negative, while positive matric potentials occurred at the 10 and 30 *cm* depths. The discontinuity between the A and B horizons in the tussock catchment that may be causing a perched water table, appears to have been broken down under the pines allowing water to percolate into the B horizon, and thereby causing the matric potentials of the lower layers to be similar to the surface layers during wet periods.

Isopleths of averaged matric potentials for the two vegetation covers show a contrast in hydrologic regimes (Figure 4.4). In the tussock catchment, the soil profile is near saturation for most of the summer: for short periods there is saturation to depths in excess of 30 *cm*, and at the same time some drying appears to be occurring at the base of the profile, with matric potentials lower than $-100\ mb$ (Figure 4.4a). The forested soil shows long periods of water deficit, with matric potentials falling throughout the profile (Figure 4.4b). The contrast between forest and tussock is very similar to differences in soil water regimes found by Pyatt and Smith (1983) who compared sitka spruce with natural grass cover, and the comparison of forest with heathland by Pyatt and Craven (1979).

Major wetting fronts have been interpreted and they vary between vegetation types in depth of penetration (Figure 4.4). Generally wetting fronts penetrated to shallower depths under the pine forest, particularly when the profile was drier than the tussock profile. Water held closer to the surface would also be more likely to be transpirated, and this would compound the differences in matric potentials at the lower depths. The greater interception loss reported by Fahey and Watson (1991) and Murray *et al.* (1991) would also reduce the water reaching the soil surface under pine.

There is a contrast in the rooting systems of the two vegetation covers. Snow tussock

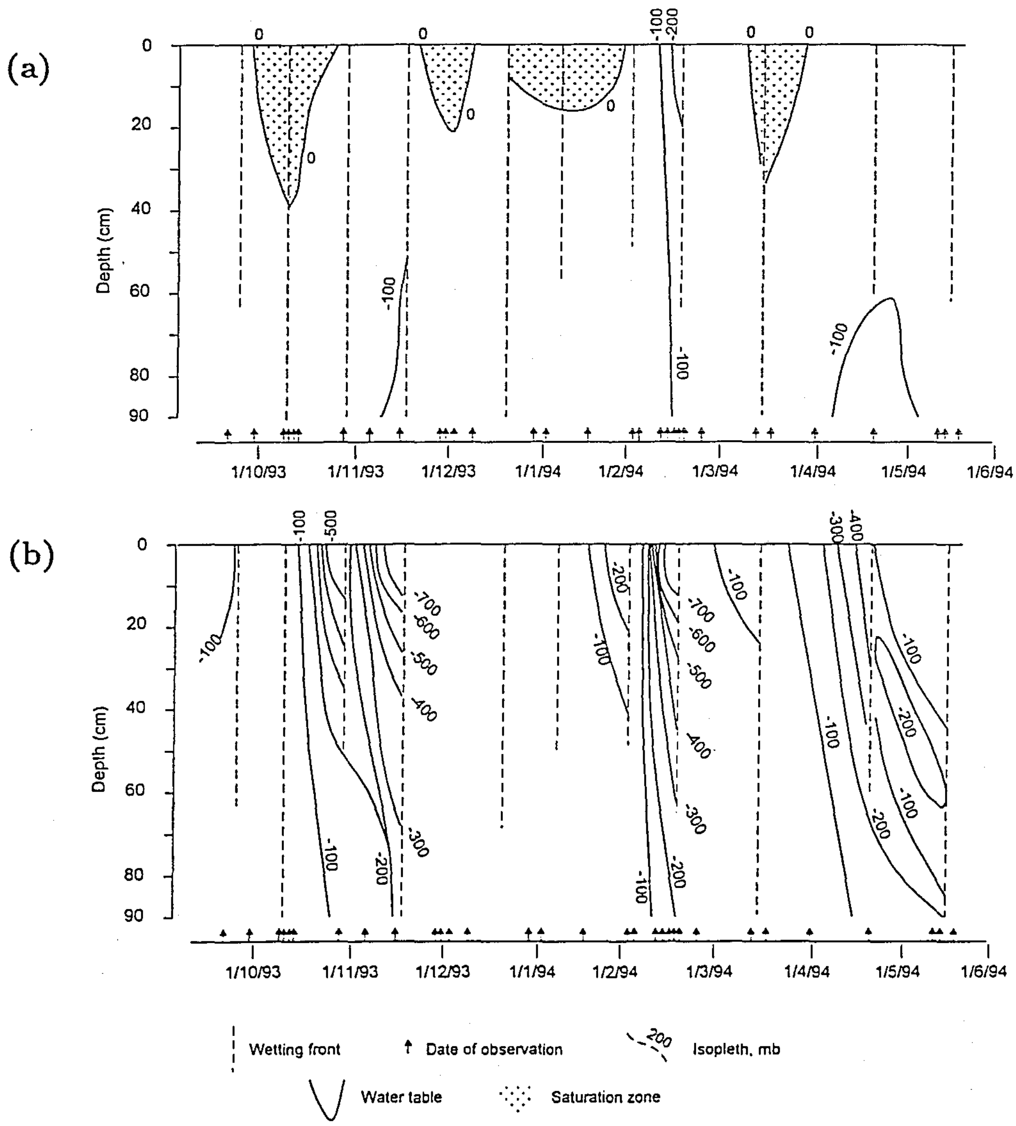

FIGURE 4.4: Interpolated matric potential isopleths, calculated from averaged tensiometer data: (a) tussock interfluve sites; (b) pine interfluve sites.

plants usually have more than 80% of their roots in the top 40 *cm* of the profile, and most of their water requirements come from this layer (Mark, pers. comm.)[2]. In contrast, the root systems of *Pinus radiata* are far more extensive. In an unpublished study of rooting patterns of *P. radiata* near Gisborne, the top 50 *cm* of the profile for 16 year old trees contained 75% of total root mass, while the 50 to 100 *cm* layer only contained an extra 5% (Watson pers. comm.)[3]. Water extraction to wilting point has been recorded under trees to a depth of 5.6 *m* (Eastham and Rose, 1988), though the shallow depth of the profile at Glendhu would not allow root systems to reach this depth.

The difference in the depth of soil water extraction between tussock and pine soil profiles during drying events is shown for the periods 13/10/93 – 17/11/93 in Figure 4.5 and 18/1/94 – 17/2/94 in Figure 4.6. During the October/November drying period the tussock differs from the pine by drying slowly, with matric potentials falling fairly evenly throughout the profile suggesting that water demands during spring are negligible and that drainage of the profile was occurring. The pine profile has matric potentials falling 700 *mb* within one month at the surface, but the decrease is less at depth. Under both tussock and pine wetting from the 35 *mm* rainfall of the 31st November 1993 does not occur below 60 *cm* in depth. A similar pattern occurs in the February drying period, although increased drying occurred in the upper tussock profile with matric potentials of less than $-200\,mb$ being recorded. The drying sequence under the pine canopy resembled closely the October/November sequence, with lowering of potentials at the 90 *cm* depth being nearly as large as that for the 10 *cm* depth under tussock.

Tree roots may colonise the soil completely, though water uptake is almost completely restricted to the upper layers of the profile until matric potentials drop below the plants' 'specific thresholds' (Waring and Schlesinger, 1985). Once this point is reached water is extracted progressively from the lower layers (Gardner, 1983; Kienzle and Schulze, 1992).

It is generally accepted that evaporation from forest exceeds evaporation from grassland over long periods. Dunin (1982) attributed this partly to the greater depth of rooting of forest in regions experiencing water deficiencies. He concluded that even though forests may possess deeper roots and have enhanced interception loss it does not necessarily follow that forests will exceed grasslands in rates of evapotranspiration, because of complex reasons such as soil water supply, leaf area, and leaf age.

As a result of the work by Campbell (1987), it is clear that narrow-leaved snow tussock (*Chionochloa rigida*) is conservative in its water use. Transpiration is subject

[2]Personal communication with Prof. Alan Mark, Botany Department, University of Otago.

[3]Personal communication with Mr Alex Watson, Landcare Research, Christchurch.

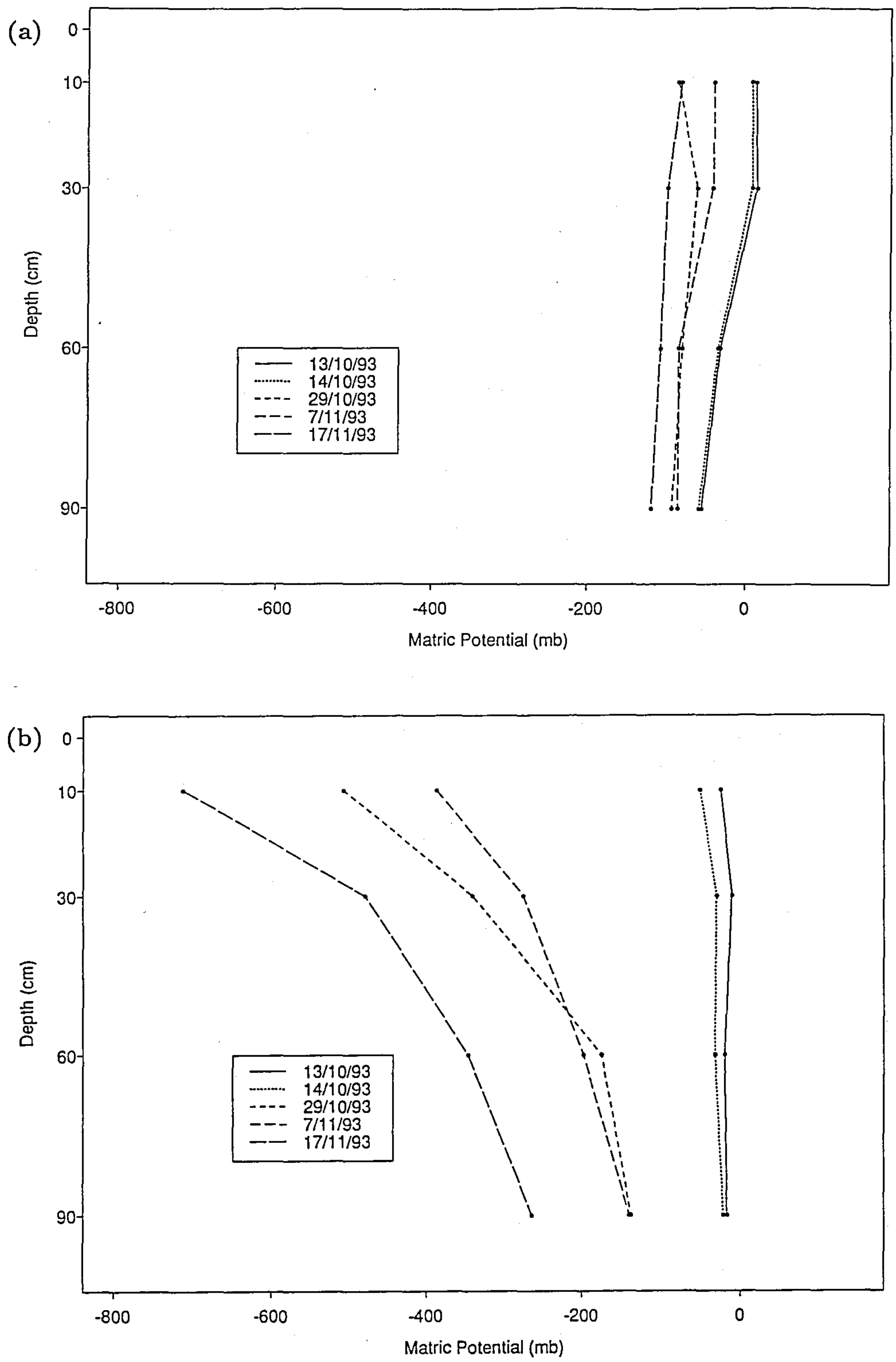

FIGURE 4.5: Average matric potential profiles during October and November 1993: (a) tussock interfluve sites; (b) pine interfluve sites.

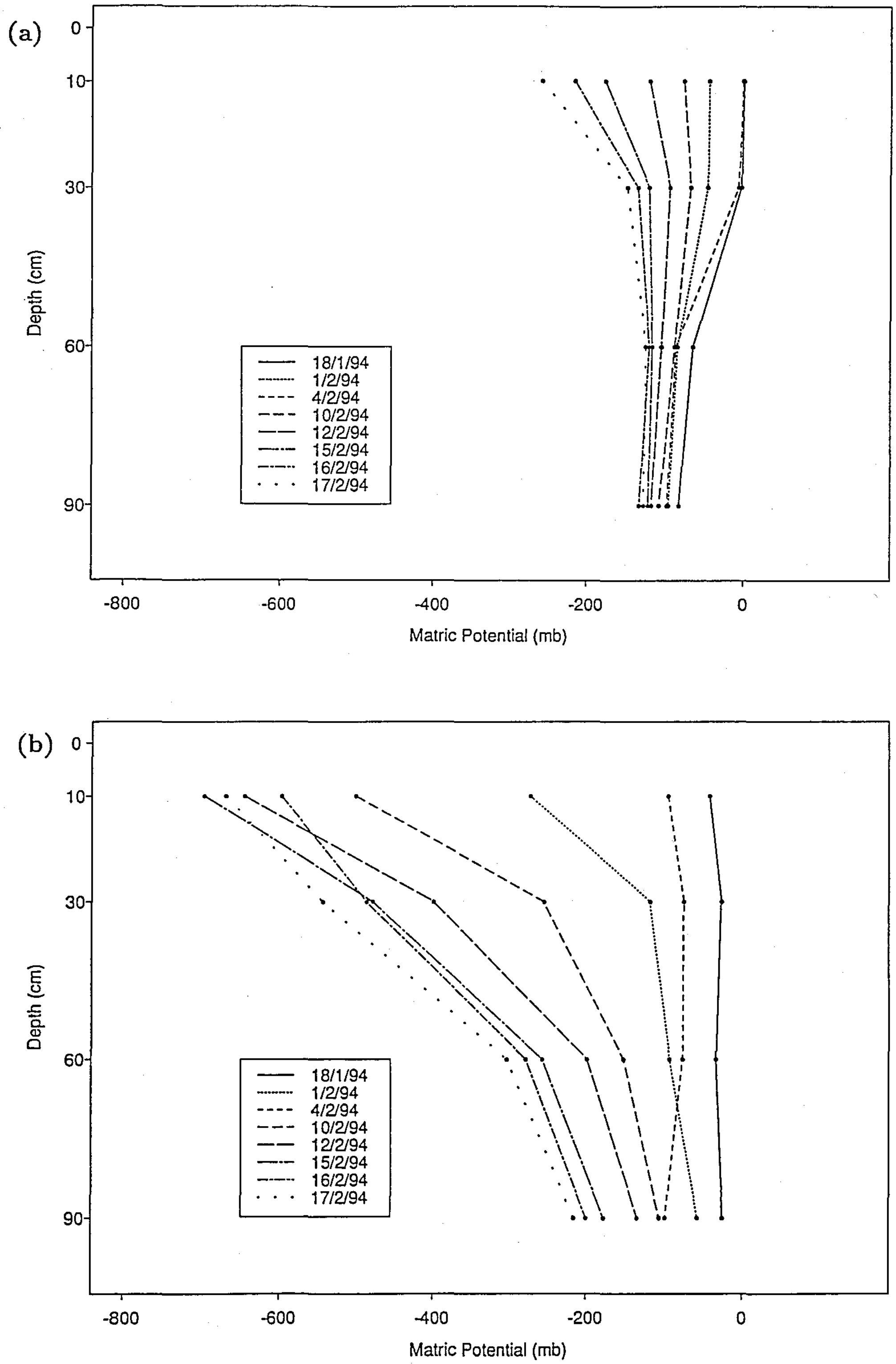

FIGURE 4.6: Average matric potential profiles during January and February 1994: (a) tussock interfluve sites; (b) pine interfluve sites.

to high levels of physiological control, and rates are less than those found for typical pastures and crops, but similar to those of *Pinus radiata*. As a result of the lower interception by tussock, more water reaches the A horizon, from where tussock draws most of its water, conservative though it may be. On the other hand the pine will be forced to draw water from deeper in the profile to fulfil its transpiration needs, as interception loss reduces water inputs at the surface.

Total potentials

When comparing averages of total potentials recorded at the tussock and pine interfluve tensiometer nests, differences in the direction of the vertical moisture fluxes may be interpreted (Figure 4.7). The dominating pattern within the tussock soil profiles is for a downward moisture flux, with the exception of February and to a lesser extent the beginning of November, where the tendency for water redistribution in the top 30 cm is upward as evaporation demand increases (Figure 4.7a). During the spring and summer drying periods for the averaged soil profile under the forest cover, total potentials indicate an upward flow from the 90 cm layer (Figure 4.7b). Partial reversal of the downward flux occurs at other times, with drying at 10 cm drawing water from the 30 cm region, though the downward flux remains in the lower profile. During April 1994, drying occurred under the pines and the flux direction was upwards, though rain during this period was sufficient to wet the A horizon and initiate a downward flux between the 10 and 30 cm depths. During this period, there was no reversal of the flux gradient for the averaged tussock profile.

Tussock dry canopy evaporation rates vary considerably with season. Campbell (1987) showed mean monthly dry canopy evaporation rates for snow tussock at Glendhu to be more than $3 mmd^{-1}$ for January, and under $1 mmd^{-1}$ between May and September, but found that these seasonal variations were related largely to changes in saturation deficit, rather than to solar radiation. These differences are apparent in the response of total potentials over the study period. The first drying period in November saw some responses in the upper layers, with the flux profile inverted, but during the February dry spell, the depth of drying increased when transpiration rates may have been higher. In April, when transpiration rates as estimated by Campbell (1987) would be lower, the lack of an upward water flux indicates that little drying occurred at the surface.

Complete reversal of the flux under the pine during both main drying events with water moving upwards from the 90 cm depth, indicates significant transpiration during both spring and summer. During the autumn, spacing of the data does not allow the maximum drying at the 10 cm depth to be ascertained, as rain wetted the top of the

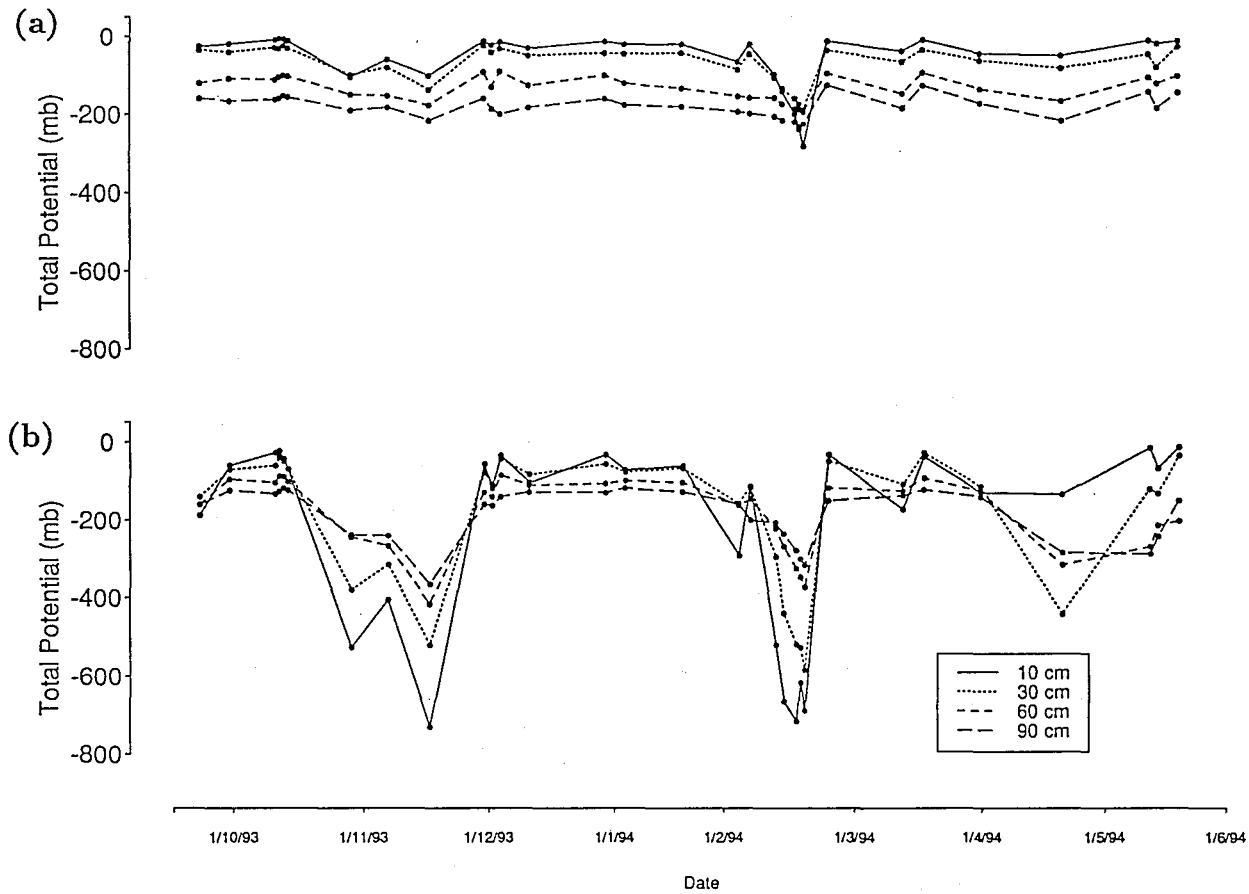

FIGURE 4.7: Comparison of average total potentials: (a) tussock interfluve sites; (b) pine interfluve sites.

profile just before the recording in late April. The upward moisture flux from 90 *cm* does indicate that drying during autumn was quite substantial, and may have been near the magnitude of the earlier drying events.

Soil water storage

Several days after rain, drainage almost ceases, and water is held in the soil pores by capillary and osmotic forces. At this stage, the soil is said to be at 'field capacity', which is the maximum amount of water that a freely drained soil can store (Dunne and Leopold, 1978). Storage opportunity[4] was calculated from the selected datum water contents on the January 18^{th} 1994 for both vegetations. This date is three days after

[4] Full listings of the neutron probe counts used to calculate water content and storage opportunity are given in Appendix A.

the last significant rainfall, and is considered to represent the storage ability of the profile after rapid runoff and drainage of excess precipitation has occurred. During the previous week precipitation of 40 mm was recorded, which fully wetted up the soil profile, thereby allowing a datum storage capacity to be established. Water stored in excess of this datum may occur during or shortly after rainfall, but will not contribute to long term storage in the soil profile.

At the datum date, the average water storage under the pine forest was 7 mm less than under tussock for the profile of 0–100 cm depth. The averages for the tussock catchment were calculated with the exclusion of the tussock middle site left tube, because it was not the same length as the other tubes. For the 0–40 cm layer, the tussock actually had a 28 mm greater storage, but for the 40–100 cm layer, the pine held 21 mm more water in storage. On December 11^{th} 1993, again three days after significant rain, the soil water status of the catchments was close to the datum levels, and averages of storage opportunity throughout the interfluve show the soil profile had drained to the point where the tussock 0–40 cm layer contained 30 mm more water than the equivalent layer under the pine. Again the 40–100 cm layer under the pines contained more than the tussock, but the difference at 14 mm was not as large.

Greater storage following several days drainage under tussock would be expected if the pines had increased the macroporosity of the upper A horizon. The energy required to exceed the capillary forces holding water in larger pores is less than that required to remove water from the smaller pores. Therefore, with the visual differences in structure, and the higher water storage at the date chosen to represent near 'field capacity' conditions, it appears that the storage potential of the A horizon of soils under pines is less than that under tussock. The difference in magnitude of storage under the pine in the lower layer is harder to explain. The greater extent of the root system is unlikely to be seen by the neutron probe, though increased organic matter and therefore hydrogen ions could increase probe counts. Structural changes within the soil resulting from the pine root system may have allowed water to drain from the A horizon into the B quicker than under the tussock, as a result of the breakdown of the structural discontinuity between the horizons. Consideration must be given to the variable nature of the material making up the profiles at Glendhu, and changes in storage, especially in the B horizon, may not be related to the vegetation cover.

Average storage opportunities of around 15 to 20 mm developed during October and February respectively for the whole profile under tussock cover (Figure 4.2c), but the 40–100 cm section of the profile remained very close to 'field capacity' throughout the data collection period. Storage opportunity for the pine sites (Figure 4.3c) is up to twice that for the tussock interfluve sites during drying periods, with substantial water extraction occurring from the 40–100 cm layer.

Storage opportunity reacts inversely to changes in matric potential, as would be expected, and the contrast between the two vegetation covers is as large as that observed in the matric potentials. Storage opportunity changes indicate the inactivity of the B horizon in the tussock catchment with total storage opportunity for the profile being almost entirely the result of water loss from the A horizon. In a sandy soil under short vegetation, the intermediate zone between the main root system and the capillary fringe would be expected to remain at 'field capacity' if no water was being consumed by plant roots, and water movement would be negligible within the soil, as strong adhesive and capillary forces hold water in the finer pores (Kienzle and Schulze, 1992).

Using change in moisture content between successive readings, total evaporation loss from the soil profile was calculated by assuming it to be equal to rainfall and the decrease in soil moisture content during the period. The major abstraction of water from the profile below field capacity is by evapotranspiration (Dunne and Leopold, 1978), and percolation and runoff are assumed to be negligible as the periods chosen have storage values less than datum storage. This method has been applied in loess soil in the lower South Island by Watt (1976).

For the period 4^{th}–10^{th} February 1994, mean evaporation rates of $1.2\,mm\,d^{-1}$ and $1.0\,mm\,d^{-1}$ were calculated for the tussock and pine catchments respectively. For the period 10^{th}–16^{th} February 1994, the tussock catchment reveals a lower mean evaporation rate of $0.5\,mm\,d^{-1}$, and pine increasing slightly with a mean rate of $1.3\,mm\,d^{-1}$. While Campbell (1987) calculated mean interception loss for tussock at 21%, and interception by pine at Glendhu is in the order of 30% of gross rainfall (Fahey and Watson, 1991), corrections to rainfall to estimate transpiration loss, given that precipitation was $2.2\,mm$ and $0.6\,mm$ for the first and second period respectively, makes little alteration to the mean evaporation rates calculated. Essentially rates calculated will be close to dry canopy transpiration rates which are considered to be similar (e.g. Campbell, 1987; Murray *et al.,* 1990). Reduction in evaporation rates later in the drying period for tussock may be related to the reduction in matric potentials near the surface where the majority of the root mass is located (Figure 4.2). Water stress may be imposed on the tussock root system near the surface, and the lack of deep penetrating roots may have reduced the evaporation rate in comparison with pine.

For individual tubes in the pine catchment, all evaporation rates fell within the 0.5 to $3.5\,mm\,d^{-1}$ range that is generally expected for *Pinus radiata* in New Zealand (Kelliher, pers. comm.)[5], but generally rates appear low for this time of the year. The same may be said for tussock evaporation rates when compared with figures given in Campbell (1987), but as no data on the saturation deficit or energy balance are available for these periods of time, detailed interpretation of these data sets is not possible.

4.2 Topographic effects

4.2.1 Interfluve sites

Tensiometer nest averages were taken for each of the three tussock interfluve sites. For the upper site, 58% and 50% of all matric potentials recorded for the 10 and 30 *cm* depths respectively were positive, indicating saturation at these times, while the middle site experienced saturation on 58% and 48% of all recordings at the 10 and 30 *cm* depths. At the lower site, only 32% of recordings at the 10 *cm* depth showed saturation, while only 1 recorded matric potential out of 31 at the 30 *cm* depth was positive. The tussock upper site varied least at all depths, and the drying events had the least effect on matric potentials at the 10 *cm* and 30 *cm* depths when compared with the two lower tussock interfluve sites (Figure 4.8).

The interfluve slope sites differ from many hill slope profiles in that the longitudinal profile is convex rather than concave. The average slope running beneath the upper, middle and lower sites is 12, 18, and 43 degrees respectively. If a uniform hydraulic conductivity exists throughout the slope, saturated subsurface flow will be directly proportional to the hydraulic gradient (Ward and Robinson, 1990). Downslope there is a greater reduction in matric potentials during drying periods in the 10 and 30 *cm* layers. The 60 *cm* and 90 *cm* layers also differed downslope, with maximum and minimum potentials decreasing and saturation not being reached. The increasing slope, and the associated increase in hydraulic gradient, may see water removed from the profile more quickly than at upper slope positions.

Water storage at the datum date of the 18^{th} January 1994, for both the upper and middle interfluves shows no difference, although the lower site held an extra 10 *mm* of water on that date. On the 11^{th} December 1993 when the profiles were close to the datum storage, both the lower and middle interfluve sites held the same amount of water as on the 18^{th} January 1994, but with the upper site holding 8 *mm* less than the middle, and 18 *mm* less than the lower site.

On the 10^{th} February 1994, which is the last day of complete neutron probe records

[5]Personal communication with Dr Frank Kelliher, Landcare Research, Christchurch.

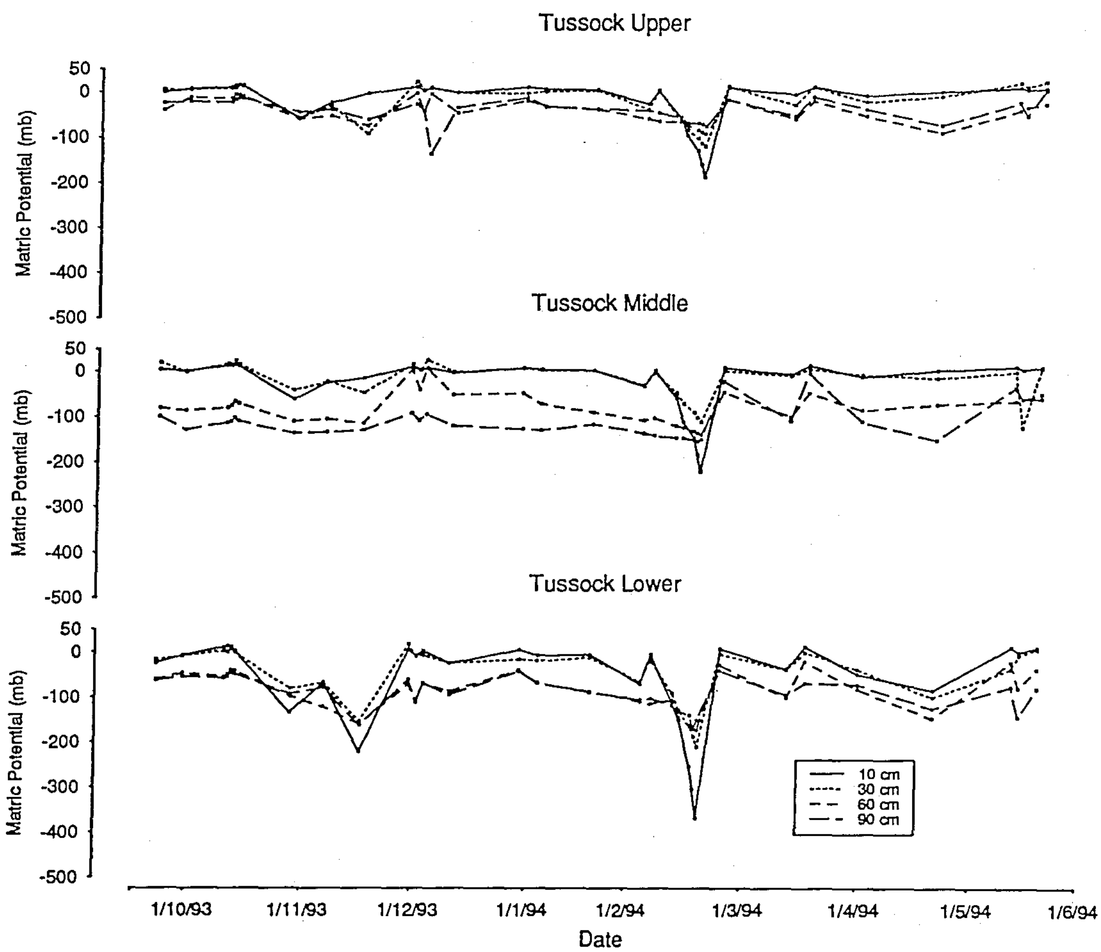

FIGURE 4.8: Matric potential averages at the three tussock interfluve sites.

for the February drying period, there was also downslope increase in moisture content in the tussock interfluve. As matric potentials indicate, the surface is drier further down the slope, but storage in the B horizon is of sufficient magnitude to produce a downslope moisture gradient, although this is reduced in size. Solar insolation would be greatest at this site because of the slope, and the greater drying in the surface layers may be related to this. The pattern seen here appears unusual in that the upper site is saturated in the A horizon while at 'field capacity', whereas the lower site is not near saturation at 'field capacity', though it holds more water in storage. Detailed examination of the physical properties of the different profiles may be required to determine the reason for this phenomenon.

Storage opportunity comparisons for the three different interfluve sites show no obvious differences during the study period (Figure 4.9). Storage opportunity reacts in the

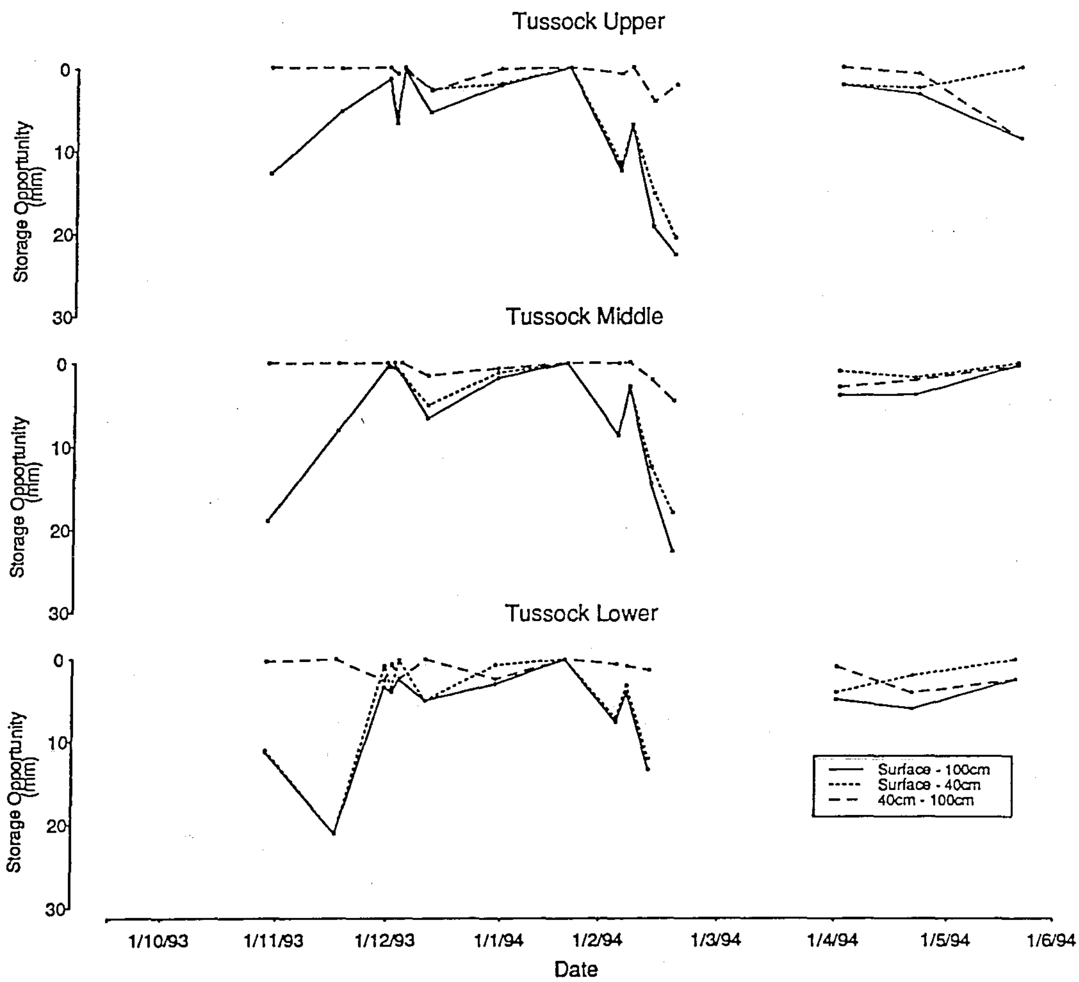

FIGURE 4.9: Storage opportunity averages at the three tussock interfluve sites.

same direction, with similar opportunities developing at the three different topographic locations, but the datum values that they deviate from decrease upslope. Even with the convex nature of the interfluve, the theoretical gradient of moisture discussed by Helvey *et al.* (1972) would appear to exist in this situation.

A comparison of the total potentials between the three interfluve sites is given in Figure 4.10. At the tussock upper site, decreasing total potentials from the 10 *cm* to the 90 *cm* depths were maintained throughout the study period, except for a short period during February 1994 when the flux was directed upwards between the 10 and 30 *cm* depths. Flux direction at the top 30 *cm* of the tussock middle site profile was upwards during the summer, and to a lesser extent during spring drying periods, though the 60 and 90 *cm* depths still maintained the downward flux on all but three occasions. Here wetting was occurring from the base of the profile. The largest upward gradient

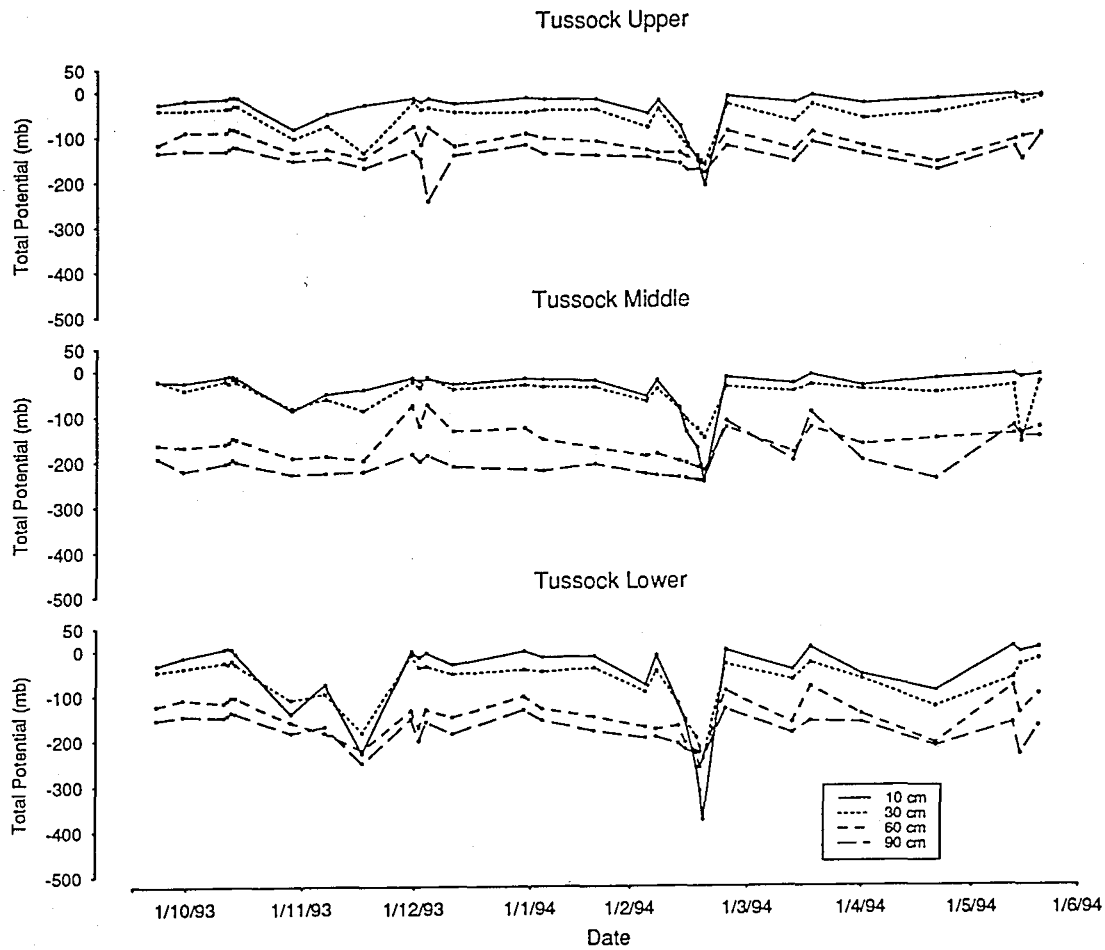

FIGURE 4.10: Total potentials calculated from nest averages of tensiometer data at the three tussock interfluve sites.

occurred on the 18^{th} May, 1994 after 25 mm of rain had fallen in the previous week. The only other observation of this phenomenon occurred at the tussock lower site. The shallower profile at the tussock middle site may contribute to this upward wetting, as flow downslope converges at this point.

The interfluve has the potential to contribute to stormflow from the catchment through saturated overland flow. Lower slopes have the ability to hold more water, with upper slope sites at or near saturation while at 'field capacity', and given that storage opportunities that developed at different locations in the slope are similar, saturation overland flow is more likely upslope.

4.2.2 Headwall sites

The headwall sites are wetter than interfluve sites, with surface layers experiencing saturation for long periods of time (Figure 4.11). As with the interfluve sites, there appears to be some evidence for a perching layer at the base of the A horizon. The headwall has a similar convex profile, with average slope below each tensiometer nest being 10, 14, 15, 18, and 31 degrees for headwall sites 1 to 5 respectively. But there is convergence at lower slope sites because of the concave planar morphology. Under the classification of Kirkby and Chorley (1967) the transect in the headwall lies in the centre of a slope concavity in plane. Convergence of subsurface flow in the centre of the concavity may lead to flow rates in excess of the transmission capacity of the soil.

At headwall site 3 the 60 and 90 *cm* depths showed substantially lower matric potentials[6] than those in the A horizon, while the 30 *cm* depth has equal or greater matric potentials than at 10 *cm* depth throughout the study period. Only 43% and 35% of matric potentials recorded at the 10 *cm* and 30 *cm* layer respectively were negative, indicating saturation for substantial periods of time. Headwall site 4 showed a similar pattern, having negative matric potentials for 28% of all recordings taken at the 30 *cm* depth. At the 30 *cm* depth at headwall site 5, 55% of all recordings were negative. The upper slope site of headwall 1 and headwall 2 showed saturation in the top 30 *cm*, but for reduced periods of time.

Subsurface flow rates may increase with increasing slope, but with increasing concentration of water as a result of the concave planar form of the headwall, the length of time that the A horizon is saturated increases progressively downslope. Headwall site 5 is the exception to this, but still has significant periods of saturation at the base of the A horizon, though the break of slope immediately below the site may cause subsurface flow rates sufficiently large to remove inflows.

Results from a throughflow study running simultaneously beside the tensiometer nests in the headwall slope showed flow rates in the moss and A horizon were more than 6 times greater at the base of the slope. The moss and A horizons also contributed most of the subsurface flow in the slope (Bowden, pers. comm.)[7]. The convergence effect of the slope morphology is clear, and there are larger amounts of water moving through the lower slope profile.

A small water deficit occurred during the February drying period, and minimum matric potentials in the headwall at the 10 *cm* depth ranged from -150 to just over

[6] Matric potentials for the headwall nests are contained in Appendix B.

[7] Personal communication with Prof. William Bowden, Department of Natural Resources, University of New Hampshire.

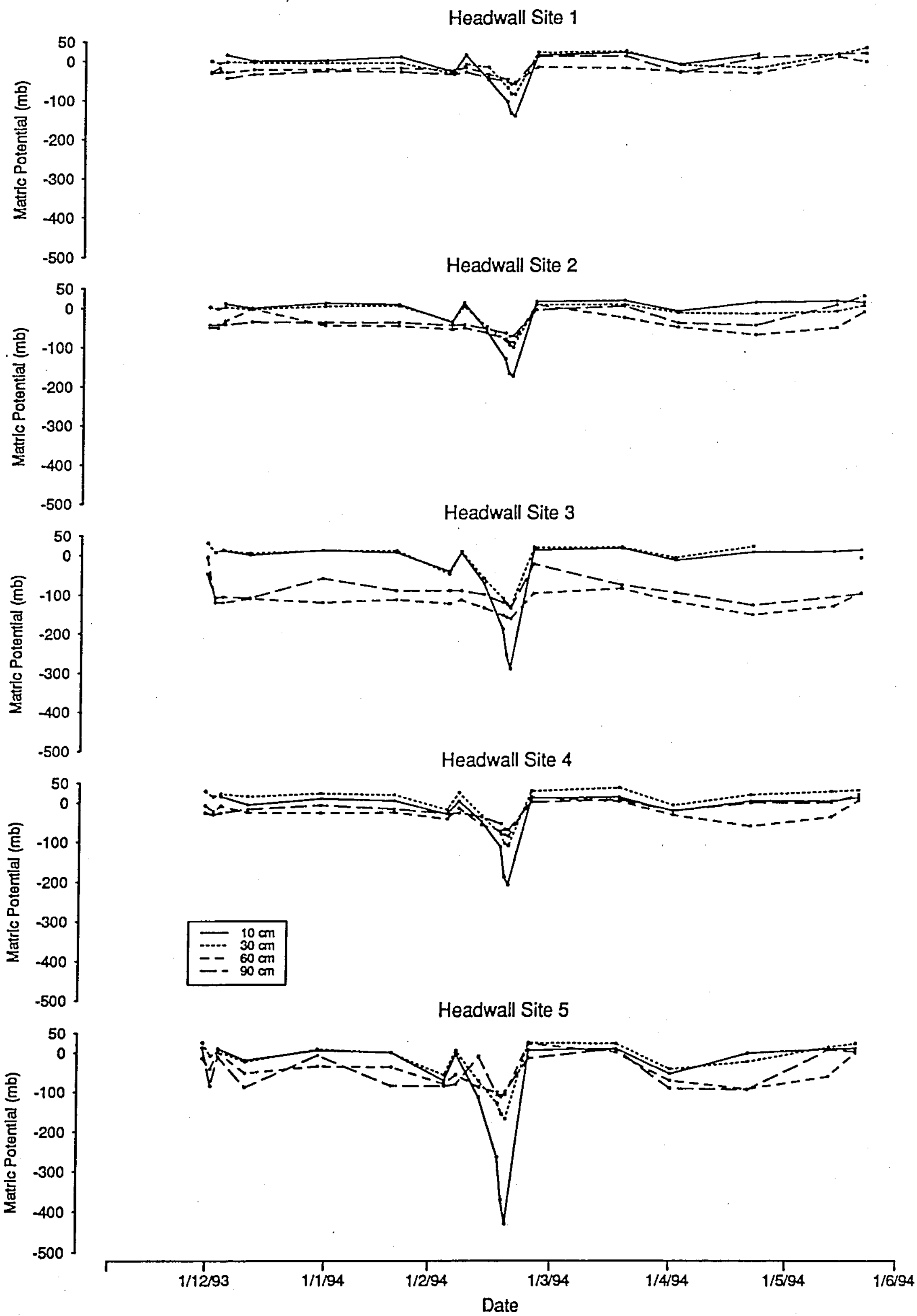

FIGURE 4.11: Matric potentials at the wetland headwall sites.

$-500\,mb$ (Figure 4.11). The greatest drying at $10\,cm$ occurred at the base of the slope at headwall site 5, with headwall site 3 reaching -300 mb. As with the interfluve sites, the least variation in matric potentials for each depth occurred the highest site above the wetland with the least slope, which is headwall site 1. Headwall site 3 had the greatest range of matric potentials at the 30 and 60 cm depths, with headwall site 5 having the greatest range at the 10 and $90cm$ depths. Headwall site 4 showed considerable variation in the A horizon, though movement of potentials during the study period at the 60 and 90 cm depths was very similar to the headwall sites 1 and 2.

Discontinuities between the A and B horizons appear to be important in the dynamics of the headwall slope. While the time interval between recordings in the headwall slope was too great to monitor changes during storm events, it is clear that most of the changes in the water status of the slope occur in the A horizon. There is no pattern related to topographic position, except that the sites with low slope have low variability. With the evaporation demands under tussock being small, the main changes in the soil water status of the profile will be inputs through precipitation, and outputs through drainage. In the case of the upper slope sites where the hydraulic gradients are low in comparison with lower slope sites, the profile will not drain as quickly. The upper slope sites because of their position in the concavity will also not receive large subsurface or surface flow inputs, leading to lower variation in matric potentials.

Headwall site 5 is unusual because of the high range of matric potentials at the 10 cm depth. The maximum matric potential recorded at this layer was 10 mb and this was the lowest maximum at this depth for the whole slope. Variation at the lower depths was also greater than for all other slope sites, with large changes at the 90 cm depth. The density of snow tussock at site 5 was less than that of the other sites on the slope and there was a mixture of *Sphagnum spp.* and grasses forming the main ground cover around this nest. This may mean that this site receives greater solar insolation at the surface. Sphagnum moss can have extremely high evaporation rates (Nichols and Brown, 1980), and these factors and slope, rather than topographic position may have caused the high variation of surface matric potentials. At the base of the B horizon of site 5, there was also a layer of heavily weathered *in situ* schist, which would have high hydraulic conductivity and may allow water to drain quickly into the wetland.

The total potentials suggest that water moved up the profile at site 5 at times during the study period, as the 90 cm layer has higher total potential than the 60 cm layer (Figure 4.12). This is not linked to evaporation loss at these times, as the gradient in the upper horizons is not reversed and water will tend to move from the $10cm$ to the $30cm$ layer. In the week previous to May 14^{th} 1994, more than $20\,mm$ of rain fell. On this date

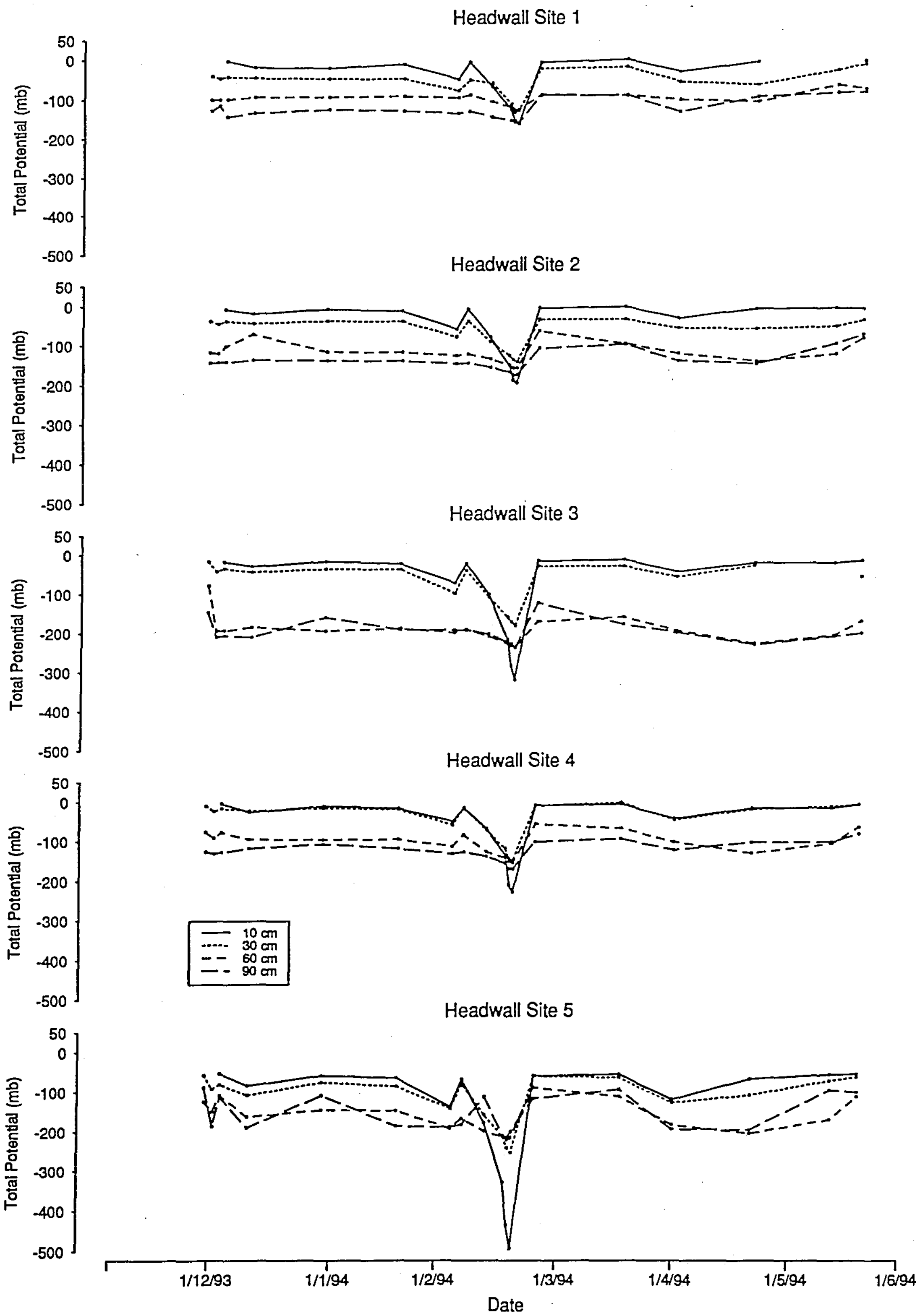

FIGURE 4.12: Total potentials at the wetland headwall sites.

one of the largest upward gradients developed at the base of the site 5 profile, and this will occur when the wetting front at depth is determined by downslope flow, rather than vertical infiltration, at this location. When a profile wets, rapid movement at depth can generate complex wetting patterns, which may include wetting of a profile from above while wetting from below is also occurring (Wheater *et al.,* 1990). The weathered schist layer at the base of the B horizon may have a greater hydraulic conductivity than the soil material at 60 *cm* depth, and water moving downslope during lateral flow following a rain event may arrive at the base of the profile from upslope before vertical infiltration works through the B material. At all headwall sites there are periods during which water tends to move from the 90 to the 60 *cm* layer, driven by differences in total potential (Figure 4.12), but this did not occur during periods of high evaporation when the flux was upward in the upper layers, indicating that this phenomenon is linked to wetting of the slope profile.

The storm pattern was very complex throughout the study period which makes interpretation of the wetting patterns throughout the slope difficult. It is impossible to determine and monitor the growth of any saturated wedge upslope, as describe by Weyman (1973), because of the spacing of the tensiometer nest and the time interval between measurements. Higher variation in the matric potentials in the lower slope indicates that changes did occur in water contents at the lower sites during the study period.

The headwall of the wetland was near, or at saturation for most of the study period, and is likely to respond to storm events quickly because the A horizon has little available storage. Bonell *et al.* (1990) identified 'old' water from the unconfined groundwater reservoir as making up a substantial part of the Glendhu catchments' storm hydrograph and pre-event water was found to respond first in the storm hydrograph. The addition of rainfall to headwall surfaces may cause saturated overland flow, but for this new water to become quickflow, a saturated link must exist to the channel. Surface storage in the wetland may be enough to prevent this occurring, at least immediately, but translatory flow will release 'old' water as the hydraulic gradient is increased by 'new' water inputs at the head of the wetland.

The recession at Glendhu has a distinct break in it, marking the point where the rapid recession after about 12–14 hours ends and a slower recession begins. By the definition of Hewlett and Hibbert (1967) quickflow ceases shortly after the beginning of the slow recession (Bonell *et al.,* 1990). Flow in the slower recession has been shown by Bonell *et al.* (1990) to consist of well mixed 'old' water. Saturated and unsaturated flows from hillslopes such as the headwall, where antecedent wetness is high, are likely to contribute significantly to the translatory flow processes that are releasing 'old' water to the stream network.

4.3 Wetland hydrology

4.3.1 Physical characteristics of the GH1 subcatchment wetland

Mean bulk densities and total porosity for the top 30 *cm* for are given in Table 4.5. The mean bulk density is very low for the GH1 subcatchment wetland, and by the classification of Verry and Boelter (1979) these surface peats would be classified fibric, of which approximately 70% of their oven dried weight would be fibre $> 0.1\ mm$. The porosity reflects the low bulk density, and these peats have a very high water holding capacity.

TABLE 4.5: Mean bulk density and total porosity with standard errors for peat cores taken from GH1 subcatchment wetland.

	Mean	Standard Error
Bulk density gcm^{-3}	0.0412	0.0034
Total porosity 0–300 *mm*	0.8812	0.0079

While the total porosity of the top 30 *cm* of the peat profile may be more than 80%, the drainable porosity is less. Taking the upper 30 *cm* of the profile and dividing it into three equal sections, there is a wide range of drainable porosities encountered. Means and standard errors are given for these three layers in Table 4.6. A series of Mann-Whitney tests reveals that there is a reduction in drainable porosity with depth. Drainable porosity for both the 0–100 *mm* and the 100–200 *mm* layers is greater than the 200–300 *mm* ($p > 0.05$). There was no statistical difference between the 0–100 *mm* and 100–200 *mm* layers. There was a clear change of structure in the top 30 *cm* of the wetland peat material, with a thick layer of *Sphagnum spp.* that had not been decomposed at the surface. This can be seen in Figure 4.13.

Given that any losses of water out of this profile after initial drainage are likely to be dominated by evaporation, the wetland does not have the ability to release a large volume of water, especially if the percentage drainable porosity at atmospheric pressure continues to decrease with depth.

A Terrain Intersection Model (TIN), created from the wetland probe survey data

TABLE 4.6: Mean drainable porosity with standard errors for different depths from GH1 subcatchment wetland peat cores.

Depth	Mean Porosity	Standard Error
0–100 mm	30.56	2.40
100–200 mm	28.12	5.44
200–300 mm	15.45	1.70

FIGURE 4.13: A section of peat from the surface layer of the tussock subcatchment wetland (Photo: Prof. W. Bowden).

using ARC/INFO geographic information system software calculates the peat volume of the tussock subcatchment wetland as 6544 m^3. From this model, contour bands of peat depth have been created and a diagrammatic representation of peat depth within the wetland is shown in Figure 4.14. The bog has pits of peat surrounded by hard layers of what is thought to be bedrock. The greater part of the bog has a surface slope of $0 - 5^o$ and the remainder except for the bottom tip has a slope of $5 - 10^o$, so these pits will not be able to drain if the surrounding material is impermeable.

4.3.2 Water table responses in the wetland

Water tables fluctuated within the GH1 subcatchment wetland, with the direction of change being the same at all five observation wells, although the magnitude of change did differ (Figure 4.15). The water table fell during the main streamflow recession periods at Glendhu, and there appears to be a synchronous decline in matric potentials in the headwall slope (Figure 4.11). Maximum water table decline from the highest recorded position was at observation well A, where water levels fell 34 *cm*. The minimum recorded fluctuation was 23 *cm*, and was recorded at well B, with the average of the five wells being 27.5 *cm*. At all wells, the water table reached, or exceeded, the bog surface by several centimetres on occasions.

Measurements of the surface position indicate some shrinkage of the peat as the water table fell, but maximum fall was only 7 *cm*. After rewetting of the peat profile, peat volume swelled again, and surface height usually returned to its original position.

The synchronous decline in water tables and matric potentials in the headwall slope, indicates that surface and subsurface inputs may be important in the maintenance of water levels in the bog. Without intensive investigation of the groundwater system, there is no means of determining the role of this potential input. Water table fluctuations are likely to be highly variable, with substantial inputs from storm events generating runoff from saturated areas on the surrounding slopes.

Given the laterally confined nature of the wetland, during periods of significant input water tables will intersect the surface of the bog, and saturated overland flow will occur. This was observed during and after several large rainfalls during the study period. Bonell *et al.* (1990) placed some significance on surface storage abilities of the wetlands at Glendhu, which had to be exceeded before 'new' water from the storm event could be released to the channel. Precipitation intensity was shown by Bonell *et al.* (1990) to be a major factor in determining if the wetland storage capacity was exceeded and saturated overland flow initiated. Residual storage capacity was not high throughout the study period as a result of the unusually wet summer at Glendhu, and saturated

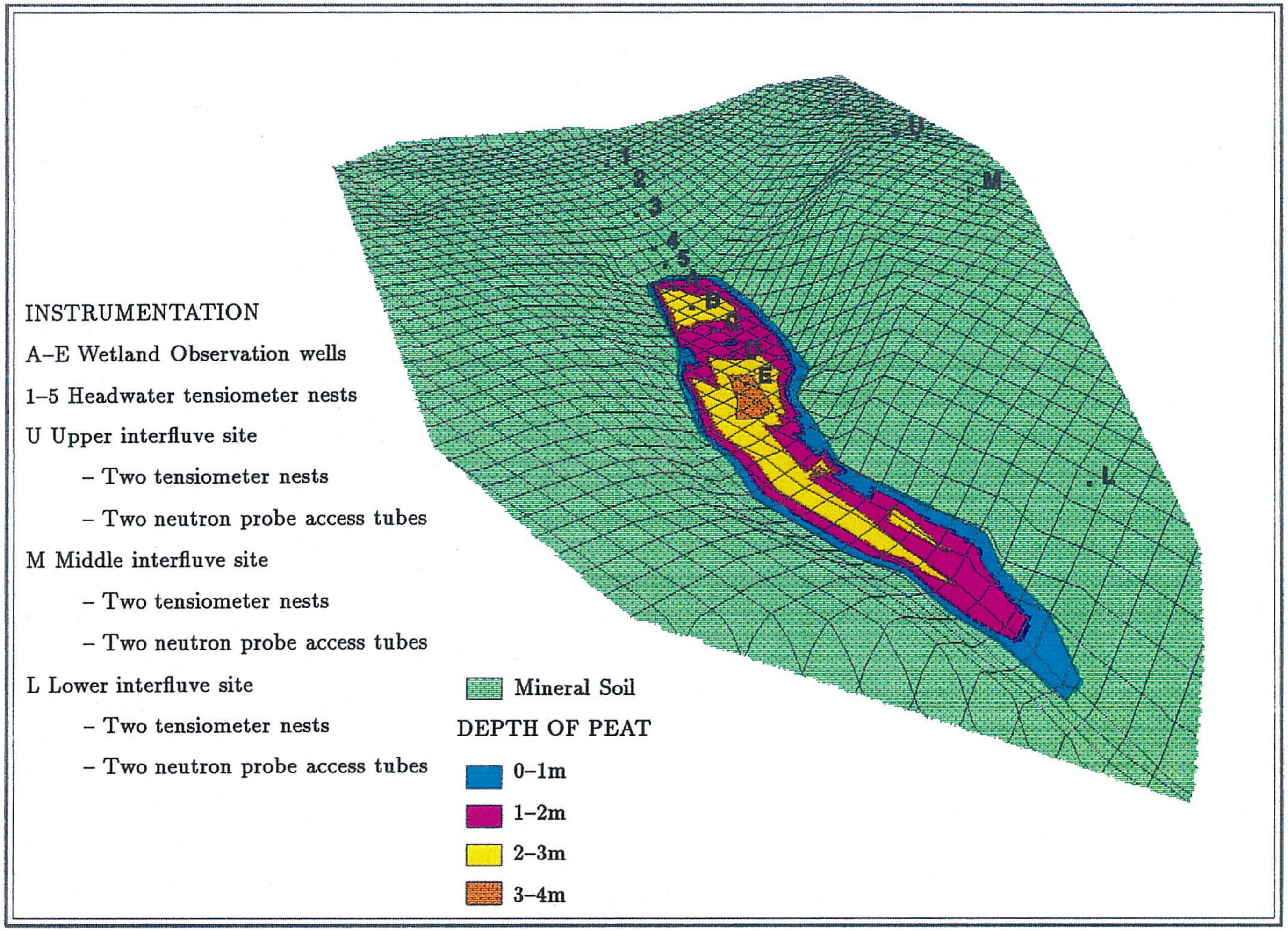

FIGURE 4.14: The tussock subcatchment, showing depths of peat in wetland as interpolated from a TIN model of probe survey data.

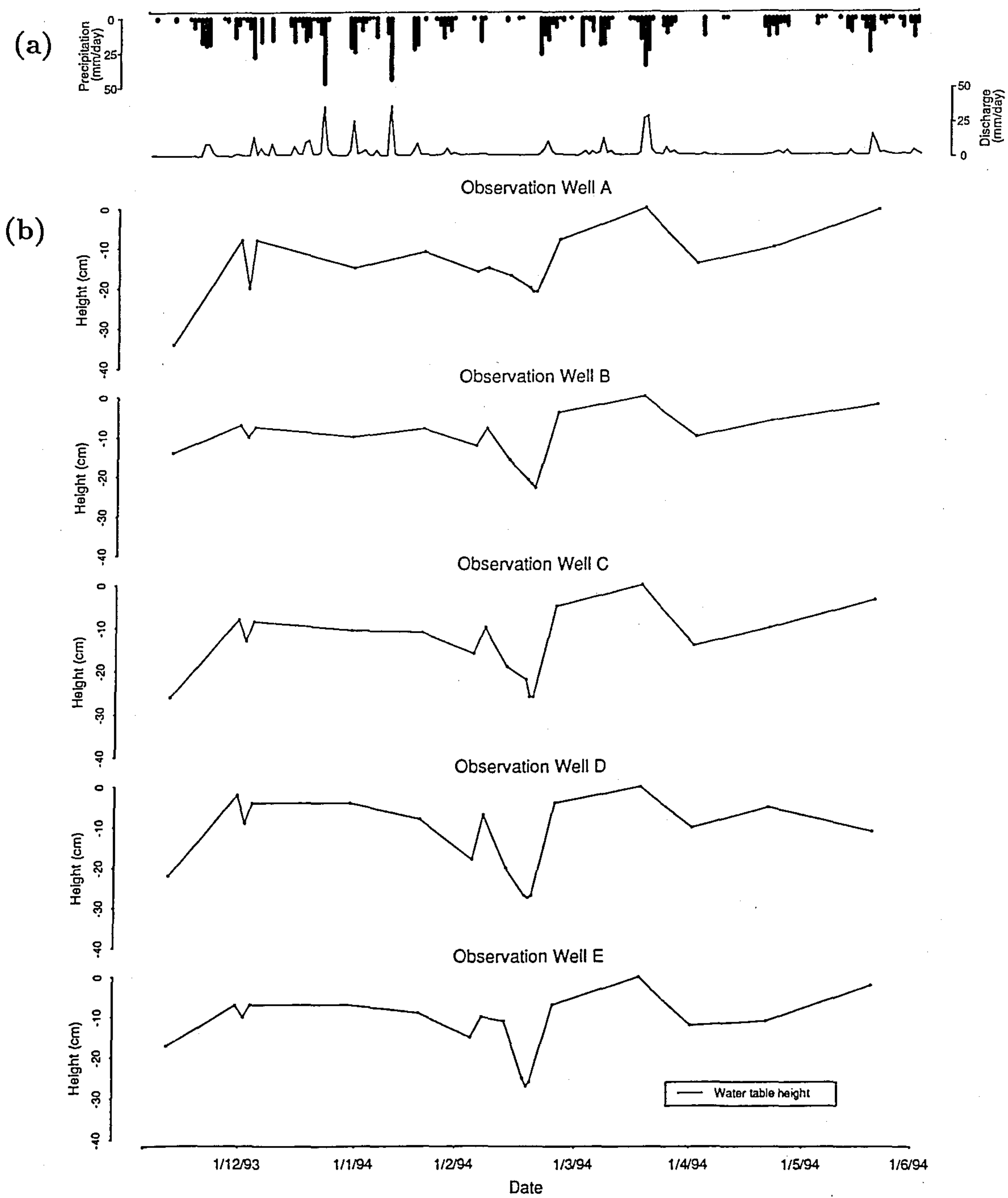

FIGURE 4.15: Wetland water table observations during study period: (a) rainfall and discharge at tussock catchment weir; (b) fluctuations from maximum recorded for water table and surface height.

overland flow at the surface of the bog is likely to have occurred during many of the larger storms.

The time interval does not allow close monitoring of the high frequency fluctuations in the wetland, but longer time trends may be interpreted. Given the average size of the fluctuations, and the drainable porosity of the material, it is possible to calculate the amount of water released from the wetland for declines in water table level. Using the average drainable porosity figures calculated, 70 mm of water would be removed from the wetland if the water table fell on average 27.5 cm. Assuming that this wetland behaves in the same manner as all wetlands in the tussock catchment, the number of days for which catchment baseflow could be sustained from the source above is less than one week. It would seem likely that the wetlands are conduits for, rather than sources of, baseflow.

5

Summary and Conclusions

5.1 Summary

An investigation was conducted into three aspects of the soil water regimes at the Glendhu experimental catchments, east Otago, New Zealand: soil water changes after the native *Chionochloa rigida* grasslands had been over planted in *Pinus radiata* forest; the effect of the characteristic topography on soil water regimes; and a preliminary investigation into some of the physical and hydrological characteristics of a peat wetland.

Soil physical properties of both the mineral soil and the wetland peat were analysed. Data on the soil water regimes in both the tussock and pine catchments were collected between October 1993 and May 1994. They included matric and total potentials from 17 tensiometer nests, 6 in the pine catchment and the remainder under tussock cover. There were 6 neutron probe access tubes in each catchment, and differences in soil moisture content were calculated for periods during the study. Wetland water table fluctuations were also monitored between December 1993 and May 1994 using 5 observation wells located in a wetland adjacent to the tussock tensiometer nests.

Analysis of soil water data showed differences in the seasonal and short term soil water regimes between the *Chionochloa rigida* and *Pinus radiata* soil profiles. Soil water patterns were identified in relation to topographic features in the tussock catchment. Investigation of the physical and hydrological properties of the peatland, together with information collected from the surrounding mineral soils has provided information on the possible role of these wetlands in some of the unique hydrological characteristics of the region, such as high sustained baseflows and high 'old' water content in stormflows.

5.2 Conclusions

- Average water storage capacity is greater in the top 40 *cm* of the tussock soil profile. There appears to be structural changes in the A horizon under *Pinus radiata* leading to an increase in the number of large pore spaces in the soil, though differences in bulk density were not found in the limited sample taken. The A horizon under tussock cover remained saturated for long periods of time, while saturation was not experienced under forest cover. A perched water table at the base of the A horizon under *Chionochloa rigida* may be a result of structural discontinuities between horizons, whereas under *P. radiata* this discontinuity may have been broken down.

- Greater drying of the soil profile occurred under *Pinus radiata* when compared with *Chionochloa rigida*. Larger water deficits developed in the *P. radiata* profile with significant water extraction occurring from the B horizon. Differences in root systems appear to allow water extraction from greater depth during times of high evaporation demand. Vertical water movement in the profile was often upwards under the forest, and this is attributed to greater interception loss from the *P. radiata*, thereby reducing water availability in the main zone of water uptake for the trees, which is near the surface.

- Seasonal differences in drying between the different vegetation covers were found, with large water deficits developing during spring, summer, and autumn in the forested soil, but only during February in the tussock profile, and to a lesser extent than under the pine. This cannot necessarily be attributed to differences in evaporation, as transpiration dominates during dry periods, and rates are theoretically similar for *Pinus radiata* and *Chionochloa rigida*. There may be another underlying process that is yet to be determined which causes these differences.

- There is a contrast between the headwall and interfluve soil water regimes of the tussock catchment. The lower headwall sites are considerably wetter than the interfluve because of the convergence effect of the concave planar form. The convex profile, with increasing slope towards the toe of the interfluve, allows faster subsurface flow rates, and reduces the time the A horizon is saturated. Saturated overland flow is more likely to occur in the headwall of the wetland, although there are long periods of time when it may occur at the interfluve sites. Potential saturated flow source areas do not appear to be connected with the stream network.

- There was an increasing moisture content downslope during both wet and dry periods under tussock. While the lower sites held more water, saturation of the A horizon occurred upslope, suggesting that there is a difference in the storage capacity of the soil that may be related to slope.

- The water table of the peat wetland only fluctuated 27.5 *cm* during the course of this study, and a fluctuation of this size, if consistent over the catchment, would not sustain baseflow from the region for more than one week. Water levels in the wetland appear to be linked to the water status of the surrounding slopes. Both saturation overland flow, and saturated and unsaturated subsurface flow contribute water to the wetland. It appears that the wetlands in the region may not be the cause of the sustained baseflow, but rather a consequence of this. Water storage in the unconfined soil water reservoir being released through processes of saturated and unsaturated flow are the likely cause of the high baseflows in the region. The wetland had storage opportunity available for most of the study period, and may attenuate saturated overland flow from the surrounding slopes, which is a possible cause of the dominant 'old' water signature of storm and baseflows at the Glendhu catchments.

- The pine catchment showed no signs of saturation throughout the study period. Flow from the slopes surrounding wetlands, through saturated overland and subsurface flows, will be less than for the tussock catchment, and storage opportunity in the wetlands may be increased due to lower wetland water tables. This scenario accords with the results of Fahey and Watson (1991), who found reduced peak flows from the planted catchment. Baseflows will also be lower as less water will be moving out of regolith storage, thereby reducing the translatory flow processes believed to be delivering water to the stream channel in the region.

5.3 Future research

There are many different areas of the hydrology of the Glendhu region that would warrant further investigation, and some of these are:

- Investigation of the soil physical properties that may have been affected by afforestation, e.g. soil hydraulic conductivity, bulk density, and volume of pore space drained at various matric potentials. Study of the degeneration of any structural discontinuity between the A and B horizons that may have reduced saturation of the A horizon in the pine catchment.

- Identification of soil water storage differences at 'field capacity' with slope position and slope.

- The addition of a weir at the GH1 subcatchment or similar catchments, supplemented by increased numbers of throughflow pits to cover the different topographic units present. This would allow water balance calculations for the wetland and surrounding slopes. With information gained from automatic tensiometers and neutron probe or time domain reflectrometry (TDR) technology measuring water content of the slopes, a more detailed understanding of the runoff mechanisms, water storage, and released characteristics of the wetland could be gained.

- Investigation of differences in wetland hydrology between the two catchments, to determine changes that may affect quickflow and baseflow regime differences between catchments.

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Appendices

Appendix A

Interfluve neutron probe counts and matric potential data

The first neutron probe was used between 29/10/93 and 16/2/94 and had a standard count in a water tank of 1325. The second neutron probe was used between the 18/3/94 and 19/5/94 and had a standard count in water of 1239. The symbol ND is used to represent missing data.

TABLE A.1: Pine lower site neutron probe counts.

	DEPTH (*cm*)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	236	631	746	730	688	680	716	730	740	717
17/11/93	236	596	709	691	696	657	682	710	709	685
30/11/93	294	750	801	770	834	725	705	742	725	702
2/12/93	309	734	803	760	733	702	721	730	733	691
4/12/93	333	800	828	787	752	718	718	739	744	700
11/12/93	319	762	853	794	743	746	760	763	761	721
30/12/93	368	808	878	768	743	736	765	782	785	749
18/1/94	405	827	834	799	777	742	785	771	755	745
1/2/94	264	694	791	749	734	742	762	756	753	731
4/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10/2/94	763	636	743	746	709	721	740	749	747	726
16/2/94	227	623	698	711	707	688	730	742	734	708
1/4/94	571	748	743	711	706	681	725	716	715	674
21/4/94	282	653	686	674	655	637	657	699	692	671
19/5/94	361	772	761	773	741	703	664	682	699	671
Right Tube										
29/10/93	287	738	783	735	730	704	704	713	712	733
17/11/93	275	678	772	722	717	692	691	689	688	710
30/11/93	392	826	831	742	716	706	717	714	715	724
2/12/93	352	815	843	743	743	713	719	699	709	727
4/12/93	442	868	857	764	725	723	714	701	709	713
11/12/93	402	845	840	713	714	732	723	717	728	738
30/12/93	492	905	859	715	738	737	726	724	734	741
18/1/94	456	857	855	777	769	747	729	733	741	736
1/2/94	397	829	842	763	741	742	746	736	731	752
4/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10/2/94	318	786	797	749	739	731	731	721	729	750
16/2/94	281	731	781	718	723	720	733	711	728	734
1/4/94	493	811	770	726	685	683	674	693	713	703
21/4/94	341	699	721	670	683	677	677	660	675	673
19/5/94	526	877	785	720	694	670	665	688	668	612

TABLE A.2: Pine middle site neutron probe counts.

	DEPTH (*cm*)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	322	762	770	748	768	770	721	724	713	753
17/11/93	327	724	753	714	747	733	742	718	733	735
30/11/93	438	848	834	752	719	748	737	740	733	745
2/12/93	403	818	816	760	751	771	721	725	731	751
4/12/93	503	888	829	773	768	751	710	731	749	741
11/12/93	434	846	834	745	761	768	745	737	733	751
30/12/93	499	893	825	762	771	766	741	726	727	758
18/1/94	552	894	843	713	766	773	713	745	739	772
1/2/94	387	830	813	767	779	754	730	740	736	761
4/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10/2/94	375	770	796	735	757	752	721	717	714	754
16/2/94	304	732	758	725	755	755	728	719	726	732
1/4/94	507	791	756	706	730	718	696	686	688	707
21/4/94	403	750	738	680	738	691	672	686	686	676
19/5/94	509	864	726	729	716	721	678	704	679	698
Right Tube										
29/10/93	124	598	777	744	719	732	729	719	739	742
17/11/93	124	595	770	725	703	715	712	717	734	737
30/11/93	188	752	860	771	735	740	730	718	753	751
2/12/93	161	720	806	759	735	738	726	755	759	732
4/12/93	199	805	888	788	744	725	732	758	735	760
11/12/93	179	741	859	754	727	739	740	727	745	748
30/12/93	216	837	858	760	737	735	745	735	745	741
18/1/94	208	791	865	750	727	749	721	750	745	755
1/2/94	137	671	811	749	734	726	744	741	755	761
4/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
10/2/94	139	608	786	716	724	738	722	717	728	739
16/2/94	117	582	759	716	713	736	729	732	739	743
1/4/94	201	746	790	687	687	694	676	702	709	722
21/4/94	176	514	718	677	677	674	683	679	685	689
19/5/94	769	727	822	714	687	694	674	689	684	697

TABLE A.3: Pine upper site neutron probe counts.

	DEPTH (cm)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	349	799	803	784	776	758	711	722	737	737
17/11/93	338	746	791	760	753	751	700	727	710	743
30/11/93	472	877	842	803	778	751	743	733	731	765
2/12/93	447	870	822	792	798	753	737	746	750	741
4/12/93	510	923	852	786	773	748	724	730	773	734
11/12/93	452	887	814	791	777	767	719	733	725	741
30/12/93	536	920	846	786	186	742	732	753	739	735
18/1/94	491	930	846	786	797	744	731	738	744	748
1/2/94	423	836	815	779	783	753	717	712	730	763
4/2/94	476	870	828	793	792	747	740	716	747	751
10/2/94	399	805	819	756	782	736	718	728	754	751
16/2/94	346	755	791	766	759	717	721	723	728	718
1/4/94	626	797	766	719	719	693	683	683	700	704
21/4/94	377	749	738	729	717	695	685	685	673	697
19/5/94	510	870	793	753	734	716	682	686	693	692
Right Tube										
29/10/93	413	763	735	731	741	726	729	732	744	768
17/11/93	406	716	693	700	726	710	742	733	752	766
30/11/93	503	805	738	730	745	736	732	740	753	750
2/12/93	486	793	751	742	741	711	721	736	765	768
4/12/93	637	842	752	719	764	732	731	733	769	758
11/12/93	553	821	736	753	771	719	721	738	756	754
30/12/93	648	849	757	737	752	725	745	737	756	742
18/1/94	570	835	752	758	770	728	743	749	754	778
1/2/94	462	761	720	753	768	729	732	732	765	748
4/2/94	470	794	733	764	764	733	726	745	759	752
10/2/94	459	758	722	727	739	778	743	747	741	740
16/2/94	418	738	695	714	731	733	712	742	733	750
1/4/94	642	733	681	700	690	685	680	705	701	713
21/4/94	473	727	663	655	692	613	661	693	715	704
19/5/94	538	807	773	682	704	614	694	690	705	711

TABLE A.4: Tussock lower site neutron probe counts.

	DEPTH (*cm*)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	571	878	860	774	756	780	738	634	699	668
17/11/93	527	844	862	725	735	739	663	605	624	735
30/11/93	732	906	876	790	756	777	733	630	706	674
2/12/93	711	888	853	801	761	773	734	627	707	679
4/12/93	737	882	882	780	775	778	724	629	683	676
11/12/93	675	896	868	754	788	780	733	634	704	678
30/12/93	790	903	876	763	759	754	720	617	695	675
18/1/94	735	890	879	781	761	759	733	650	707	672
1/2/94	648	885	873	779	773	760	734	633	694	677
4/2/94	749	907	855	760	789	759	720	629	693	676
10/2/94	629	873	861	769	772	745	724	637	699	670
16/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1/4/94	738	825	773	709	725	733	676	605	664	612
21/4/94	748	828	791	714	705	703	662	589	643	616
19/5/94	747	862	818	739	709	727	686	579	647	626
Right Tube										
29/10/93	572	896	851	738	716	711	658	699	728	707
17/11/93	185	809	936	868	753	707	719	773	653	634
30/11/93	686	921	852	737	685	681	646	668	721	708
2/12/93	657	927	835	729	694	675	657	703	712	716
4/12/93	728	932	872	719	685	681	646	692	712	711
11/12/93	673	917	835	722	704	704	652	703	709	725
30/12/93	712	954	842	705	702	686	696	643	728	726
18/1/94	707	940	847	732	698	691	639	704	730	710
1/2/94	580	942	849	720	713	673	643	701	730	708
4/2/94	683	926	838	706	702	688	665	708	696	708
10/2/94	561	901	840	691	702	700	643	702	717	712
16/2/94	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
1/4/94	691	851	756	658	637	653	604	669	656	661
21/4/94	671	842	777	677	660	641	593	654	673	665
19/5/94	764	861	793	700	653	627	611	648	658	674

TABLE A.5: Tussock middle site neutron probe counts.

	DEPTH (*cm*)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	321	941	957	873	735	599	554	510	ND	ND
17/11/93	664	992	950	820	643	563	538	495	ND	ND
30/11/93	823	1011	945	816	661	565	531	486	ND	ND
2/12/93	811	1011	948	868	658	565	539	501	ND	ND
4/12/93	842	999	933	800	647	666	521	489	ND	ND
11/12/93	773	1007	933	801	642	544	553	497	ND	ND
30/12/93	839	1001	941	800	645	553	526	500	ND	ND
18/1/94	816	987	916	885	648	556	534	502	ND	ND
1/2/94	759	995	929	802	661	570	534	506	ND	ND
4/2/94	832	1015	945	775	650	562	533	498	ND	ND
10/2/94	721	955	925	764	652	536	524	494	ND	ND
16/2/94	671	995	913	787	617	531	525	500	ND	ND
1/4/94	829	963	834	715	593	499	481	450	ND	ND
21/4/94	767	937	870	756	597	499	482	465	ND	ND
19/5/94	852	952	875	760	617	537	483	450	ND	ND
Right Tube										
29/10/93	588	996	936	817	767	715	772	699	592	506
17/11/93	608	1010	948	816	758	691	773	696	584	509
30/11/93	724	1006	943	824	744	712	759	688	576	495
2/12/93	673	1028	959	825	748	706	740	681	563	484
4/12/93	734	1018	951	813	759	695	763	705	545	494
11/12/93	638	1017	951	803	754	710	763	619	558	496
30/12/93	729	1019	933	801	761	691	777	692	556	504
18/1/94	719	1008	944	805	751	715	756	661	565	491
1/2/94	600	975	938	810	741	708	755	697	559	495
4/2/94	696	1018	939	790	744	733	751	679	557	582
10/2/94	609	991	939	791	752	681	749	682	548	508
16/2/94	520	943	894	792	733	701	750	659	540	500
1/4/94	736	945	864	748	698	668	709	634	525	462
21/4/94	752	932	851	773	696	657	703	664	522	453
19/5/94	855	942	892	769	711	663	714	644	536	435

TABLE A.6: Tussock upper site neutron probe counts.

	DEPTH (*cm*)									
	5	15	25	35	45	55	65	75	85	95
Left Tube										
29/10/93	551	941	858	745	750	761	646	611	627	746
17/11/93	853	856	843	754	778	753	722	625	713	675
30/11/93	702	985	819	728	730	750	644	611	678	753
2/12/93	671	910	848	729	733	737	646	600	633	745
4/12/93	700	976	862	721	724	722	650	601	650	749
11/12/93	668	991	854	727	717	722	639	613	643	728
30/12/93	687	968	846	742	736	733	645	604	634	741
18/1/94	733	963	858	716	752	724	624	597	628	772
1/2/94	607	941	860	738	736	721	658	580	646	736
4/2/94	708	978	866	731	748	728	640	594	660	745
10/2/94	590	931	841	733	724	739	626	544	643	731
16/2/94	495	921	853	717	731	740	640	593	638	754
1/4/94	740	878	749	677	693	662	588	580	609	730
21/4/94	719	896	783	670	693	675	607	549	596	693
19/5/94	761	938	797	686	703	686	630	561	516	523
Right Tube										
29/10/93	188	820	973	878	737	688	721	721	659	640
17/11/93	537	908	850	727	669	705	639	702	718	720
30/11/93	251	1002	989	870	750	702	720	745	663	638
2/12/93	224	1009	916	890	736	689	715	720	668	640
4/12/93	265	1009	1005	862	752	687	717	716	659	628
11/12/93	248	937	993	875	747	693	725	717	658	628
30/12/93	284	996	990	815	741	686	723	715	665	644
18/1/94	276	993	979	870	745	694	714	714	659	617
1/2/94	185	876	959	838	754	706	722	735	654	622
4/2/94	258	917	911	831	757	618	724	705	664	645
10/2/94	181	838	951	832	736	694	714	705	685	629
16/2/94	157	780	943	850	753	676	718	712	657	629
1/4/94	273	875	917	814	678	627	676	654	603	562
21/4/94	268	839	909	824	697	643	671	676	596	581
19/5/94	319	954	899	840	710	656	699	703	631	566

TABLE A.7: Matric potentials (mb) for the pine lower site.

Date	Left Nest 10 cm	Left Nest 30 cm	Left Nest 60 cm	Left Nest 90 cm	Right Nest 10 cm	Right Nest 30 cm	Right Nest 60 cm	Right Nest 90 cm
23/9/93	-222	-125	-188	-177	-12	-60	-50	42
30/9/93	ND	-49	-18	-45	-52	-35	-27	-24
11/10/93	-8	-23	-20	-33	-3	-13	-38	-32
12/10/93	-21	-6	-27	-72	0	12	3	-4
13/10/93	-43	-22	-47	-57	-28	-2	-2	-4
14/10/93	-82	-43	-64	-57	-48	-26	-19	-13
29/10/93	ND	-681	-237	-221	-519	-162	-117	-66
7/11/93	ND	-568	-360	-255	-240	-132	-106	-72
17/11/93	ND	ND	-553	-407	-827	-291	-227	-124
30/11/93	-56	-57	-160	-176	-39	-26	-21	-21
2/12/93	-155	-105	-167	-168	-80	-56	-36	-26
4/12/93	-23	-14	-30	-117	-11	0	-3	-15
11/12/93	-98	-52	-60	-51	-62	-38	-28	-23
30/12/93	-28	-21	-24	-40	-6	-9	-24	-26
4/1/94	-82	-47	-39	-18	-49	-39	ND	-21
18/1/94	-49	-27	-32	-31	-33	-21	-19	-22
1/2/94	-405	-128	-97	-76	-141	-84	-64	-31
4/2/94	-87	-80	-84	-342	-67	-49	-43	-25
10/2/94	ND	-384	-176	-112	-317	-110	-88	-45
12/2/94	ND	-686	-252	-124	-510	-137	-108	-50
15/2/94	ND	-771	-334	-181	-635	-172	-138	-59
16/2/94	-397	-783	-363	-212	-330	-186	-148	-84
17/2/94	-459	-849	-430	-224	-670	-218	-170	-72
23/2/94	-23	-29	-82	-94	-9	-6	-9	-11
13/3/94	-185	-67	-52	-38	-75	-53	-45	-25
18/3/94	4	23	17	-49	7	8	-9	6
1/4/94	-178	-87	-75	-57	-76	-62	-52	-35
21/4/94	ND	-870	-313	-224	-193	-189	-121	-64
12/5/94	ND	-55	-241	-319	4	-118	-113	-1
14/5/94	ND	-66	-207	-238	-57	-84	-63	-36
19/5/94	ND	18	-601	-148	ND	7	-3	7

TABLE A.8: Matric potentials (mb) for the pine middle site.

Date	Left Nest 10 cm	30 cm	60 cm	90 cm	Right Nest 10 cm	30 cm	60 cm	90 cm
23/9/93	-212	-115	-82	-66	-317	-111	-66	-41
30/9/93	-36	-24	-27	-15	-41	-20	-32	-18
11/10/93	-3	-13	-38	-32	-13	-39	-40	-33
12/10/93	5	-4	-21	-21	0	-11	-23	-21
13/10/93	-7	-7	-18	-17	-23	-22	-16	-9
14/10/93	-28	-30	-30	-23	-58	-45	-33	-20
29/10/93	-457	-359	-200	-160	-608	-353	-142	-96
7/11/93	-647	-307	-193	-145	-607	-228	-113	-78
17/11/93	ND	-678	-389	-321	ND	-720	-268	-195
30/11/93	-34	-48	-45	-36	-32	-10	-30	-24
2/12/93	-91	-42	-49	-34	-73	-42	-40	-27
4/12/93	-8	8	-25	-20	-7	9	-19	-13
11/12/93	-75	-29	-33	-18	-56	-28	-30	-18
30/12/93	-7	-10	-40	-26	-10	0	-41	-16
4/1/94	-48	-28	-30	-16	-48	-21	-22	-10
18/1/94	-22	-9	-27	-18	-30	-13	-34	-23
1/2/94	-202	-104	-81	-56	-227	-115	-77	-43
4/2/94	-110	-81	-74	-53	-61	-31	-63	-33
10/2/94	-627	-294	-168	-136	-713	-236	-92	-62
12/2/94	-765	-457	-228	-186	-627	-404	-125	-79
15/2/94	-776	-569	-294	-247	-640	-524	-199	-125
16/2/94	-788	-630	-318	-266	-639	-485	-222	-148
17/2/94	-809	-692	-352	-301	-603	-643	-223	-150
23/2/94	-7	3	-47	-53	-12	1	-40	-19
13/3/94	-115	-47	-52	-39	-134	-62	-48	-18
18/3/94	7	23	-47	-47	5	13	-22	48
1/4/94	-112	-57	-30	-22	-47	-68	-51	-29
21/4/94	-121	-497	-291	-184	-24	-286	-198	-127
12/5/94	0	-49	-279	-262	18	-42	-124	-105
14/5/94	-143	-149	-186	-190	16	36	-78	-65
19/5/94	2	12	-49	-61	ND	13	-33	-3

TABLE A.9: Matric potentials (mb) for the pine upper site.

Date	Left Nest 10 cm	Left Nest 30 cm	Left Nest 60 cm	Left Nest 90 cm	Right Nest 10 cm	Right Nest 30 cm	Right Nest 60 cm	Right Nest 90 cm
23/9/93	-96	-87	-70	-53	-145	-103	-76	-54
30/9/93	-24	-26	-28	-17	-44	-30	-26	-18
11/10/93	-11	-31	-41	-33	-13	-3	-32	-24
12/10/93	-3	1	-25	-19	-3	8	-16	-14
13/10/93	-22	-8	-17	-5	-16	1	-12	-6
14/10/93	-43	-22	-20	-3	-37	-12	-19	-10
29/10/93	-407	-206	-160	-133	-528	-278	-187	-144
7/11/93	-183	-178	-222	-140	-402	-236	-190	-145
17/11/93	-599	-383	-279	-254	ND	-510	-359	-286
30/11/93	-17	-33	-39	-41	-45	-58	-60	-49
2/12/93	-59	-63	-55	-50	-139	-94	-79	-58
4/12/93	ND	-14	-28	-27	-18	-10	16	-35
11/12/93	ND	-42	-41	-22	-100	-65	-46	-26
30/12/93	ND	-20	-42	-25	-9	-31	-42	-31
4/1/94	-22	-37	-12	-16	-57	-44	-31	-11
18/1/94	-20	-29	-40	-23	-88	-55	-42	-30
1/2/94	-160	-109	-119	-69	-496	-160	-112	-64
4/2/94	-30	-73	-85	-73	-208	-129	-101	-58
10/2/94	-459	-202	-173	-132	-568	-305	-208	-141
12/2/94	-730	-287	-220	-174	ND	-420	-258	-188
15/2/94	-747	-343	-261	-213	ND	-490	-311	-237
16/2/94	-764	-349	-282	-231	-663	-485	-334	-257
17/2/94	-824	-423	-298	-260	-651	-438	-341	-285
23/2/94	-2	5	-53	-54	-19	-18	-48	-56
13/3/94	-69	-57	-64	-45	-332	-111	-62	-43
18/3/94	-8	12	-34	-30	-121	2	-37	-45
1/4/94	-91	-75	-62	-45	-152	-83	-61	-44
21/4/94	-72	-202	-271	-245	ND	-356	-274	-250
12/5/94	3	-26	-220	-228	ND	-178	-210	-196
14/5/94	-41	-107	-159	-154	9	-167	-166	-151
19/5/94	6	-6	-39	19	ND	2	-60	-92

TABLE A.10: Matric potentials (mb) for the tussock lower site.

Date	Left Nest 10 cm	Left Nest 30 cm	Left Nest 60 cm	Left Nest 90 cm	Right Nest 10 cm	Right Nest 30 cm	Right Nest 60 cm	Right Nest 90 cm
23/9/93	-31	-19	-77	-88	-16	-14	-42	-36
30/9/93	-12	-14	-59	-84	-2	-5	-32	-25
11/10/93	12	1	-71	-82	12	3	-37	-33
12/10/93	14	-4	-64	-79	14	2	-32	-28
13/10/93	7	6	-57	-68	17	8	-24	-23
14/10/93	-1	-3	-56	-72	5	0	-27	-24
29/10/93	-127	-83	-116	-113	-139	-79	-79	-71
7/11/93	-72	-76	-143	-139	-62	-58	-97	-18
17/11/93	-208	-164	-179	-162	-231	-142	-140	ND
30/11/93	3	35	-62	-101	8	0	-81	-21
2/12/93	-11	-13	-132	-138	-6	-7	-85	-81
4/12/93	0	-7	-63	-92	6	-7	-74	-43
11/12/93	-26	-25	-102	-119	-22	-23	-70	-71
30/12/93	5	-18	-12	-85	7	-12	-67	1
4/1/94	-14	-18	-79	-93	-1	-19	-56	-39
18/1/94	-8	-16	-102	-109	-2	-7	-70	-68
1/2/94	-63	-68	-125	-123	-77	-62	-93	-85
4/2/94	-8	-26	-131	-127	0	-10	-97	-77
10/2/94	-108	-91	-149	-144	-115	-88	-63	-89
12/2/94	-185	-127	-162	-156	-115	-127	-125	-104
15/2/94	-242	-158	-181	-164	-265	-172	-142	-113
16/2/94	-287	-183	-182	-167	-321	-191	-148	-171
17/2/94	-335	-203	-188	-172	-399	-217	-157	-129
23/2/94	5	-4	-6	-100	10	-3	-51	20
13/3/94	-47	-44	-116	-130	-27	-33	-83	-58
18/3/94	10	-6	16	-79	15	6	-55	-58
1/4/94	-56	-41	-100	-106	-41	-34	-63	-36
21/4/94	-6	-119	-149	-162	-162	-79	-143	-86
12/5/94	10	-55	11	-142	14	-17	-52	-6
14/5/94	-5	-14	-110	-185	6	2	-47	-99
19/5/94	9	7	-3	-130	12	6	-72	-30

TABLE A.11: Matric potentials (mb) for the tussock middle site.

Date	Left Nest				Right Nest			
	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm
23/9/93	4	7	-60	ND	5	30	-53	-100
30/9/93	2	2	-64	ND	-1	-6	-59	-129
11/10/93	16	27	-59	ND	11	7	-52	-113
12/10/93	17	23	-58	ND	15	2	-46	-110
13/10/93	15	29	-52	ND	16	16	-38	-103
14/10/93	13	20	-52	ND	12	10	-44	-109
29/10/93	-58	-43	-87	ND	-64	-41	-75	-137
7/11/93	-25	-20	-80	ND	-24	-25	-75	-134
17/11/93	0	-30	-91	ND	-31	-65	-79	-131
30/11/93	11	21	17	ND	8	7	8	-93
2/12/93	3	3	-4	ND	2	0	-46	-109
4/12/93	7	8	-5	ND	8	40	34	-96
11/12/93	-2	2	-12	ND	-5	-6	-56	-121
30/12/93	10	13	-75	ND	6	0	16	-127
4/1/94	6	7	-56	ND	3	-1	-44	-131
18/1/94	4	8	-82	ND	2	-4	-48	-117
1/2/94	-28	-24	-88	ND	-38	-37	-72	-137
4/2/94	1	4	-84	ND	2	-11	-68	-141
10/2/94	-47	-40	-97	ND	-69	-52	-81	-146
12/2/94	-88	-64	-100	ND	-136	-76	-86	-148
15/2/94	-119	-84	-104	ND	-174	-98	-95	-152
16/2/94	-141	-93	-109	ND	-226	-111	-96	-154
17/2/94	-163	-100	-111	ND	-280	-122	-100	-151
23/2/94	9	2	-77	ND	7	2	21	-22
13/3/94	-4	-6	-85	ND	-9	-13	-60	-109
18/3/94	13	9	-86	ND	13	1	27	-4
1/4/94	-10	-4	-67	ND	-14	-10	-55	-110
21/4/94	5	-5	-106	ND	0	-25	5	-152
12/5/94	12	9	-102	ND	13	-9	14	-35
14/5/94	6	-240	-95	ND	5	-7	13	-60
19/5/94	11	13	-83	ND	12	3	19	-60

TABLE A.12: Matric potentials (mb) for the tussock upper site.

Date	Left Nest				Right Nest			
	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm
23/9/93	-1	14	-40	-23	-1	-5	-40	-28
30/9/93	5	5	-40	-21	8	1	14	-24
11/10/93	9	8	-41	-23	10	6	11	-25
12/10/93	13	12	-36	-18	12	3	22	-19
13/10/93	13	14	-33	-14	14	12	18	-15
14/10/93	12	14	-32	-16	12	10	10	-15
29/10/93	-53	-57	-62	-41	-62	-63	-58	-51
7/11/93	-26	-33	-58	-37	-25	-30	-49	-43
17/11/93	-8	-86	-80	-61	-1	-100	-70	-63
30/11/93	9	17	-52	-31	10	24	43	-23
2/12/93	0	6	-55	-43	2	0	-34	-42
4/12/93	7	12	-50	-251	9	1	39	-24
11/12/93	-3	11	-52	-32	-3	-18	-44	-40
30/12/93	7	-4	-41	5	10	-4	0	-32
4/1/94	4	8	-52	-29	6	-7	-11	-38
18/1/94	2	8	-57	-33	6	-5	-20	-42
1/2/94	-31	-40	-63	-35	-24	-39	-57	-47
4/2/94	3	14	-65	-41	0	-9	-67	-53
10/2/94	-54	-62	-72	-50	-59	-65	-59	-63
12/2/94	-99	-78	-79	-53	-91	-88	-70	-87
15/2/94	-130	-92	-88	-62	-128	-113	-81	-77
16/2/94	-165	-101	-90	-64	-155	-125	-87	-81
17/2/94	-194	-108	-94	-67	-182	-134	-91	-86
23/2/94	7	28	-31	0	12	-5	-3	-36
13/3/94	-6	-27	-65	-55	-6	-30	-53	-52
18/3/94	10	21	-24	10	11	-1	-17	-33
1/4/94	-10	-27	-61	-34	-9	-18	-47	-43
21/4/94	1	21	-96	-65	-1	-41	-85	-84
12/5/94	9	26	-36	3	8	13	-47	-50
14/5/94	2	19	-38	-44	6	2	-31	-60
19/5/94	8	28	-41	11	8	18	-12	-5

Appendix B

Headwall matric potential data

TABLE B.1: Matric potentials (mb) for headwall site 1.

Date	10 cm	30 cm	60 cm	90 cm
30/11/93	ND	0	-31	-30
2/12/93	ND	-6	-31	-18
4/12/93	14	-2	-30	-45
11/12/93	0	-5	-24	-35
30/12/93	-1	-7	-24	-28
18/1/94	7	-8	-22	-31
1/2/94	-31	-37	-27	-38
4/2/94	11	-11	-20	-33
10/2/94	-51	-19	-38	-47
15/2/94	-108	-72	-51	-56
16/2/94	-137	-88	-64	-62
17/2/94	-145	-89	-57	-63
23/2/94	11	18	-19	8
18/3/94	18	21	-22	7
1/4/94	-12	-15	-32	-35
21/4/94	11	-23	-37	2
12/5/94	ND	12	4	12
19/5/94	13	28	-7	15

TABLE B.2: Matric potentials (mb) for headwall site 2.

Date	10 cm	30 cm	60 cm	90 cm
30/11/93	ND	1	-49	-44.88
2/12/93	ND	-4	-52	-43
4/12/93	9	0	-34	-43
11/12/93	-1	-4	-3	-36
30/12/93	10	2	-47	-38
18/1/94	6	1	-48	-39
1/2/94	-40	-38	-57	-46
4/2/94	9	0	-54	-46
10/2/94	-61	-50	-66	-56
15/2/94	-133	-86	-81	-67
16/2/94	-170	-97	-89	-75
17/2/94	-177	-102	-89	-74
23/2/94	12	5	4	-8
18/3/94	16	5	-27	1
1/4/94	-11	-16	-52	-40
21/4/94	10	-18	-7	-47
12/5/94	13	-12	-5	3
19/5/94	11	2	-14	25

TABLE B.3: Matric potentials (mb) for headwall site 3.

Date	10 cm	30 cm	60 cm	90 cm
30/11/93	ND	30	-6	-48
2/12/93	ND	5	-121	-109
4/12/93	9	12	-121	-107
11/12/93	-1	4	-111	-109
30/12/93	10	11	-121	-59
18/1/94	4	10	-114	-91
1/2/94	-43	-49	-124	-91
4/2/94	4	7	-116	-91
10/2/94	-73	-60	-135	-101
15/2/94	-188	-111	-154	-123
16/2/94	-256	-124	-159	-127
17/2/94	-291	-133	-16	-136
23/2/94	11	18	-98	-23
18/3/94	15	18	-85	-77
1/4/94	-15	-9	-119	-97
21/4/94	5	19	-153	-129
12/5/94	6	ND	-131	-108
19/5/94	11	-9.	-97	-100

TABLE B.4: Matric potentials (mb) for headwall site 4.

Date	10 cm	30 cm	60 cm	90 cm
30/11/93	ND	27	-7	-26
2/12/93	ND	13	-22	-31
4/12/93	14	21	-8	-27
11/12/93	-6	15	-26	-17
30/12/93	9	22	-27	-6
18/1/94	3	18	-25	-17
1/2/94	-29	-19	-43	-29
4/2/94	3	23	-14	-26
10/2/94	-48	-33	-57	-37
15/2/94	-113	-79	-72	-54
16/2/94	-189	-104	-82	-67
17/2/94	-207	-110	-86	-69
23/2/94	10	28	12	0
18/3/94	13	36	2	6
1/4/94	-22	-8	-32	-21
21/4/94	3	18	-60	-2
12/5/94	3	26	-36	-1
19/5/94	11	30	4	19

TABLE B.5: Matric potentials (mb) for headwall site 5.

Date	10 cm	30 cm	60 cm	90 cm
30/11/93	ND	25	-14	11
2/12/93	ND	-8	-40	-85
4/12/93	9	2	1	-10
11/12/93	-19	-23	-52	-88
30/12/93	5	9	-34	-6
18/1/94	0	0	-36	-84
1/2/94	-72	-57	-80	-85
4/2/94	-2	4	-56	-81
10/2/94	-113	-72	-88	-9
15/2/94	-263	-129	-101	-108
16/2/94	-371	-156	-110	-114
17/2/94	-429	-168	-106	-99
23/2/94	5	24	21	-14
18/3/94	10	21	0	8
1/4/94	-53	-41	-72	-91
21/4/94	-2	-22	-94	-94
12/5/94	8	13	-60	6
19/5/94	10	22	-1	1